PHYSICS 30

Module 3

Static Electricity

Distance Learning

Alberta EDUCATION

Physics 30

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Static Electricity

Alberta
EDUCATION

Distance
Learning

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Module 3
Static Electricity
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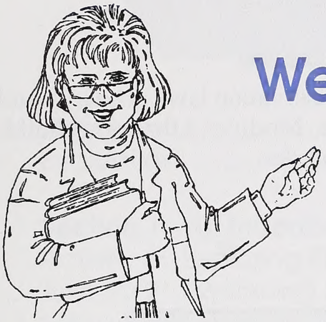


Welcome to Module 3!

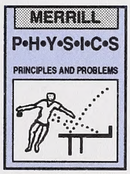
We hope you'll enjoy your study of *Static Electricity*.

To make your learning a bit easier, watch the referenced videocassettes whenever you see this icon.

You also have the option of viewing laser videodisc clips when you see the bar codes like this one.

Frame 4850A

When you see this icon, study the appropriate pages in your textbook.



Good Luck!

Course Overview

This course contains nine modules. The first two modules develop the conservation laws of energy and momentum. The conservation of energy is at the heart of the entire course. Modules 3 through 9 build one upon the other and incorporate the main ideas from the preceding modules.

The module you are working in is highlighted in a darker colour.

PHYSICS 30

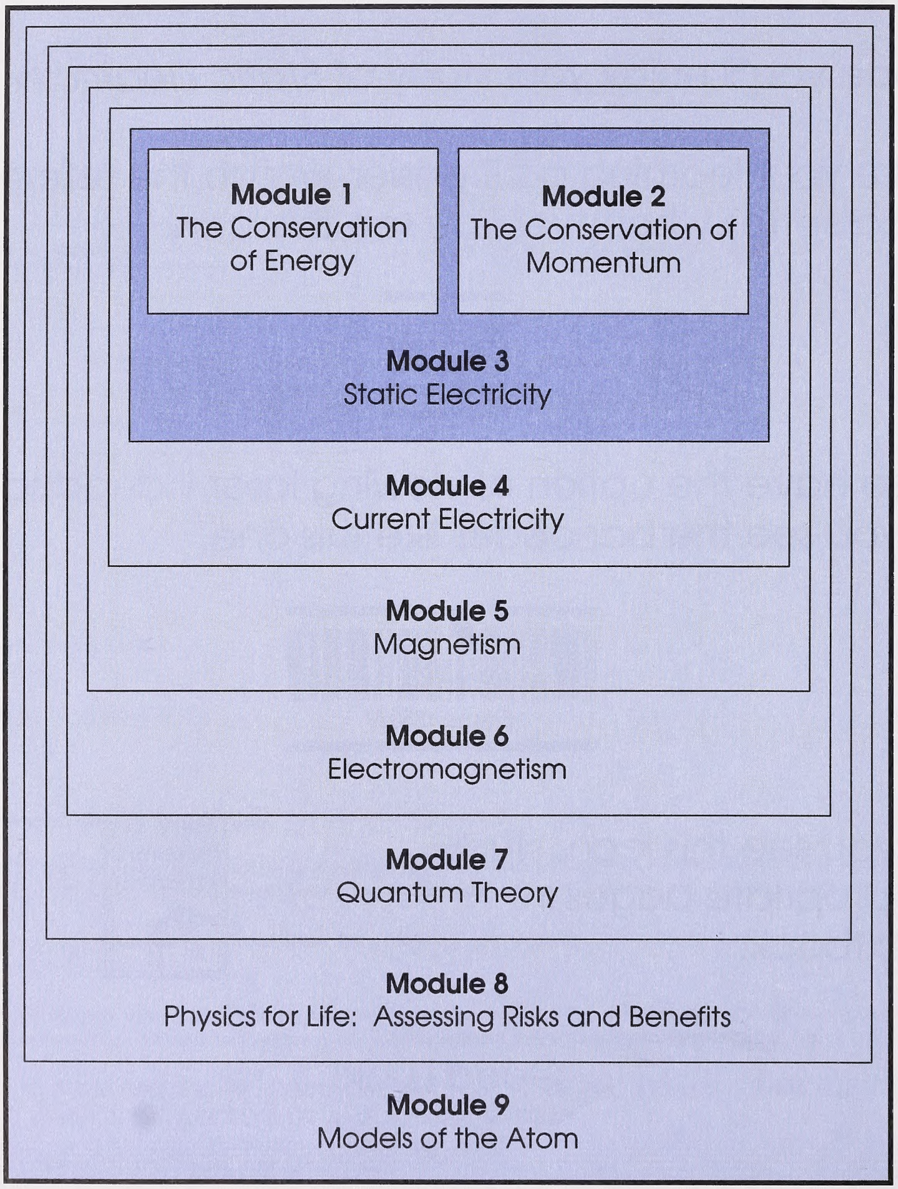


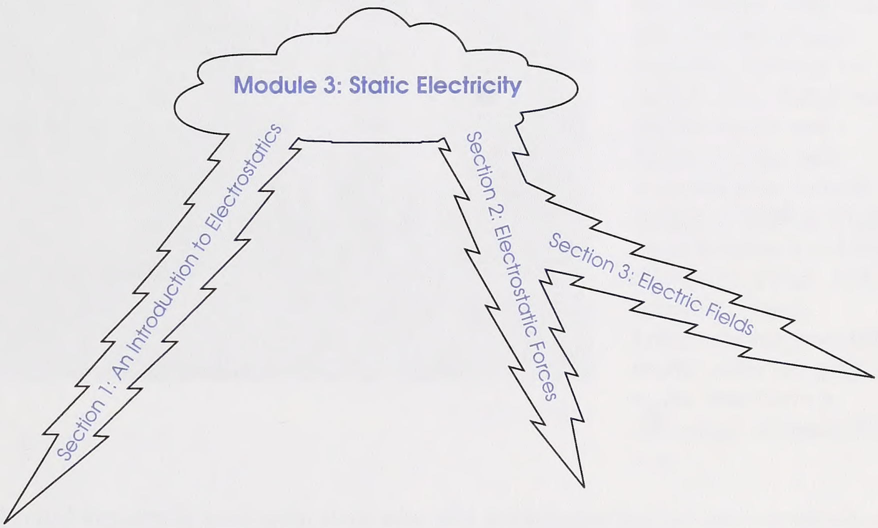
Table of Contents

OVERVIEW

The marvel of lightning bolts flashing across a cloudy sky has intrigued and mystified humans since the beginning of time. What is the cause of this powerful phenomenon? Is it similar to the sparks you observe as you stroke a cat's fur in the dark or as you reach for a door handle after walking across a carpeted floor?

Through most of history these phenomena were believed to be caused by the actions of angered gods, but, in the early 1700s scientists began to study these phenomena after realizing their potential uses and applications.

In this module you will first study how the concept of electrostatic charges evolved. Then you will study how scientists determined the forces between electrostatic charges. Finally, you will realize how a study of these charges and forces created the field theory necessary to fully understand the concept of static electricity.



Evaluation

Your mark in this module will be determined by your work in the Assignment Booklet. You must complete all assignments. In this module you are expected to complete three section assignments. The mark distribution is as follows:

Section 1 Assignment	30 marks
Section 2 Assignment	35 marks
Section 3 Assignment	35 marks
TOTAL	**100 marks**

Section

1 An Introduction to Electrostatics

THE BETTMANN ARCHIVE

Not only was Benjamin Franklin ingenious, he was also extremely lucky. The next two people who tried to duplicate this experiment were both killed.

Benjamin Franklin was the fifteenth child in a family of seventeen children. Despite the facts that his father was a candle maker and Benjamin had only received two years of formal schooling, he grew up to become a politician, diplomat, writer, and scientist. These achievements gave him world-wide recognition as the best-known American citizen of his day.

Franklin did important work with electricity and made some significant contributions. He invented the lightning rod as a way to protect buildings and he named the two types of electric charge positive and negative.

In this section you will investigate several phenomena involving the effects of static electricity. You will then refer to your observations while you develop a theory to explain static electricity.

Activity 1: Exploring Electrostatic Effects

The study of electricity was in its infancy during Franklin's time. New machines could produce large quantities of static electricity, which was stored in special jars. When the electricity left these jars, it produced a flash of light, a cracking sound, and a tremendous shock if you touched it. Franklin worked with this equipment and began to wonder if the sparks leaving the jar were actually miniature lightning bolts. He also wondered if lightning was actually a massive discharge of static electricity.

In 1752 Franklin decided to test this idea in his famous kite experiment. The kite carried a thin, pointed wire. Franklin held the kite string at the bottom with a silk ribbon. When the kite flew close to the gathering clouds of a thunderstorm, he noticed that a small key attached to the string sparked to his hand the same way that the special jar from the electricity machine did. Franklin concluded that lightning was an electrostatic effect on a planetary scale.

The artist who did the original drawing of Franklin's experiment, which is shown in the section introduction, actually has many of the details wrong. Franklin conducted his experiment as the clouds were gathering, **not** during the storm. Franklin was also indoors, holding the kite string through an open window or door and being very careful to keep the silk ribbon dry. The inaccuracies shown in this drawing may have contributed to the deaths of the two other scientists who tried the experiment later on. Franklin was saved by his precautions and by a considerable amount of good luck. Obviously you should not try this experiment yourself!

One scientist, who tried to repeat Franklin's kite experiment in his laboratory, was killed by a rare form of lightning known as ball lightning. A region of ball lightning about the size of a softball left the lightning rod in his lab and floated slowly and silently towards his face before exploding. The scientist was found dead on the floor of his laboratory with a red spot on his forehead and two small holes in the bottom of one of his shoes.

amber – yellowish fossilized tree sap that is often used in jewellery

One of the earliest experiments displaying the effects of electrostatics was probably performed by the ancient Greeks. Imagine the curiosity aroused when a piece of amber was accidentally rubbed and they saw that it could attract pieces of thread or other small objects. In this activity you will perform a similar experiment to investigate the effects of static electricity.

MERRILL P•H•Y•S•I•C•S PRINCIPLES AND PROBLEMS

Read the section called Charged Objects on pages 408 to 410 of your textbook to get a sense of how the investigation will be done. Pay special attention to the diagrams. When you have finished reading, complete the following investigation.

Science Skills

- [x] A. Initiating
- [x] B. Collecting
- [x] C. Organizing
- [x] D. Analysing
- [ ] E. Synthesizing
- [ ] F. Evaluating

Investigation: The Behaviour of Charged Objects

Purpose

In this investigation you will analyse the effects of static electricity.

Materials

You will need the following materials for this investigation:

- rubber rod and wool or fur
- glass rod and silk
- plastic comb
- four strips of Scotch Brand "Magic" ™ tape (Each strip should be approximately 18 mm × 80 mm.)

Procedure and Observations

- Read the entire Procedure and Observations section before you begin.
- Copy the following headings into your notebook. Be careful to leave enough space for your answers. Call this Table 1. Record your observations for the following steps in this chart. A completed chart will be included in the Appendix for your reference.

Table 1

The Effects of Different Objects on the Overlapping Tapes		
Object	**Effect on Tape 1**	**Effect on Tape 2**
Comb		
Rubber Rod		
Glass Rod		

MERRILL P•H•Y•S•I•C•S PRINCIPLES AND PROBLEMS

- Get two strips of tape. Each strip should be about 8 cm long. Fold about 5 mm of each piece of tape over to act as a handle. Label the pieces tape 1 and tape 2.
- Stick tape 1 to a tabletop and then stick tape 2 on top of tape 1. Refer to Figure 20-2a on page 409 of your textbook.

- Remove both strips together and then pull the strips apart. Slowly bring the strips together and observe what happens.

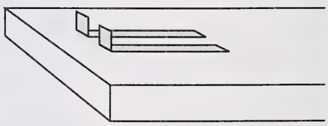
1. What did you observe as the two strips of tape slowly approached each other?

- Hang both strips of tape from the edge of a table or lamp shade, as shown in Figure 20-2b on page 409 of your textbook. Make sure the pieces of tape are a short distance apart.
- Rub a plastic comb on your clothing and bring it close to tape 1 and then close to tape 2. Record your observations on Table 1.
- Rub a rubber rod with the wool or the fur and bring the rubber rod close to each strip of tape. Record your observations on Table 1.
- Rub a glass rod with silk and bring it close to the strips of tape. Record your observations in Table 1.
- Copy the following headings into your notebook. Be careful to leave enough space for your answers. Call this Table 2. Record your observations for the following steps in this chart. A completed chart will be included in the Appendix for your reference.

Table 2

The Effects of Different Objects on the Side-by-Side Tapes		
Object	**Effect on Tape 1**	**Effect on Tape 2**
Comb		
Rubber Rod		
Glass Rod		

- Get two strips of tape, each about 8 cm long, and fold about 5 mm over to act as a handle. Stick both strips onto the tabletop side by side, as shown in the diagram. Label the pieces tape 1 and tape 2.



- Remove both strips separately, one in each hand, and then slowly bring them together.

2. What did you observe as the two tapes approached each other?

- Hang both strips from the edge of a tabletop or lamp shade, as shown in Figure 20-2b on page 409 of your textbook. Make sure the peices of tape are a short distance apart.

- Rub a plastic comb on your clothing and bring it towards each tape. Record your observations in Table 2.
- Rub a rubber rod with the wool or fur and bring the rubber rod close to each strip of tape. Record your observations in Table 2.
- Rub a glass rod with silk and bring it close to the strips of tape. Record your observations in Table 2.

Analysis

Your results should indicate that there is a special interaction between charged objects. Use your results and the information you obtained from the textbook to answer the following questions.

3. a. What must be done to the objects in this investigation before this special interaction can occur?

   b. What is the name given to this type of interaction?

   c. How did this special type of interaction derive its name?

   d. What condition is an object considered to be in after being rubbed?

4. a. How many types of charges can charged objects have?

   b. How can you justify that there are only two types of charges?

   c. Franklin gave names to the two types of charges. What did he call them?

Conclusions

5. Copy the following headings into your notebook. Be careful to leave enough space for your answers. Complete the chart by describing the behaviour exhibited by the objects being described.

Summary of the Behaviour of Charged Objects	
Description of Objects	**Behaviour**
The two objects have the same charge.	
The two objects have opposite charges.	

6. If an object can have either a positive or negative charge, can the experiment determine the type of charge held by each object?

7. If you assume that the tape pulled off the tabletop has a negative charge, you should be able to assign a charge to each object in the investigation. Copy the following headings into your notebook and complete the chart by assigning charges to each of the objects listed.

Assigning Charges to Objects		
Object	**First Part of the Investigation with Overlapping Tapes**	**Second Part of the Investigation with Side-by-Side Tapes**
Tape 1		
Tape 2		
Comb		
Rubber Rod		
Glass Rod		

8. This new force of interaction due to charged objects is called the **force of electrostatic charges**. This force is very similar to the force of gravity. However, there are also many differences between the two forces. List two differences.

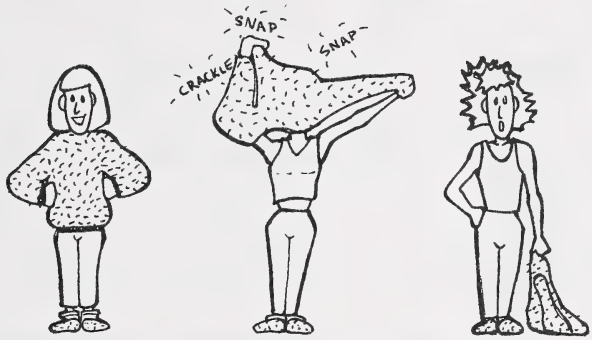
Check your answers by turning to the Appendix, Section 1: Activity 1.

The investigation that you just completed showed that the electrostatic force can be produced with very simple materials. As was mentioned earlier, the ancient Greeks were the first to record such observations when they rubbed an amber rod with a piece of cloth and watched the charged rod attract bits of leaves and dust. The word *electricity* comes from the Greek word *elektron*, which means amber. It is interesting that careful observations from such simple materials could be the starting point of the wide variety of electric effects that are the basis of so much of our modern technology. However, before you can begin to explore some of this technology, some basic questions need to be addressed first.

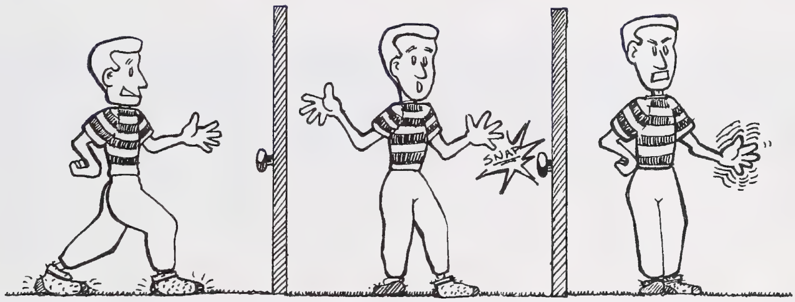
In Activity 1 you concluded that there are only two types of charges. You also observed the effects of these two charges on each other. What was the cause of these charges? You will find an answer to this question in Activity 2.

Activity 2: Explaining Electrostatic Effects

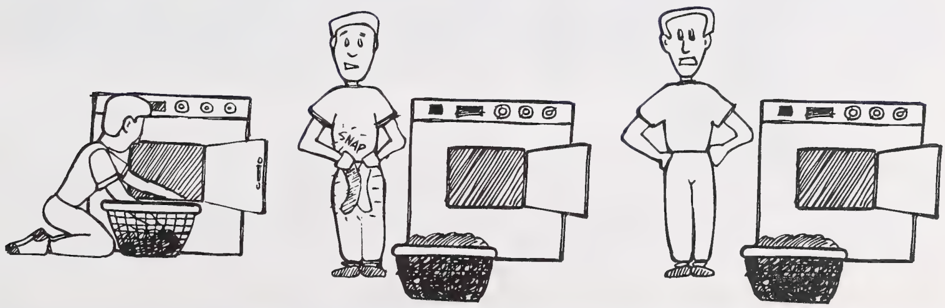
You probably encounter the effects of static electricity on a daily basis. Which of these electrostatic phenomena are familiar to you?



Wearing a wool sweater can produce static electricity. When you take off the sweater, you can hear sparks (you can see them too if your room is dark). After you take the sweater off, your hair stands on end.



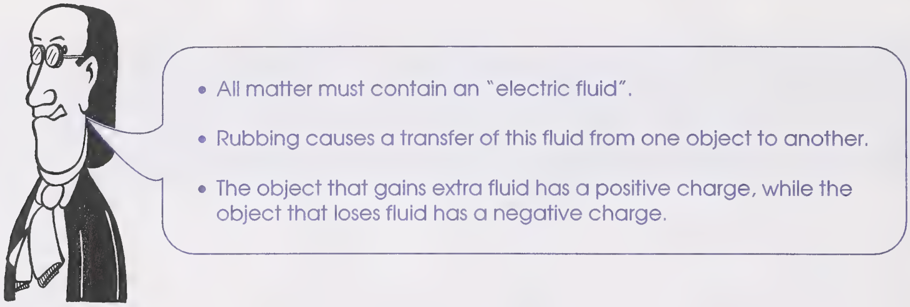
Scuffing your feet across carpet while wearing socks also produces static electricity. When you touch a metal doorknob, a spark is produced and your fingers will tingle for a while.



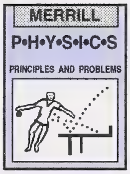
When you get your clothes out of the dryer, sometimes they are stuck together. When you pull the clothes apart, you can hear sparks snapping. Do you ever wonder how antistatic sheets work to reduce this?

These experiences all prove that objects do become electrically charged after rubbing and that once an object is electrically charged, it may attract or repel other objects. The effects of static electricity are easily observed, but what causes these electrostatic charges to develop in the first place?

Benjamin Franklin tried to explain the cause of electrostatic charges.



This fluid model for electrostatic charges was quite consistent with the thinking of that time and lasted until the late 1800s, when the origin of electrostatic charges was discovered to be charged particles, not fluids.



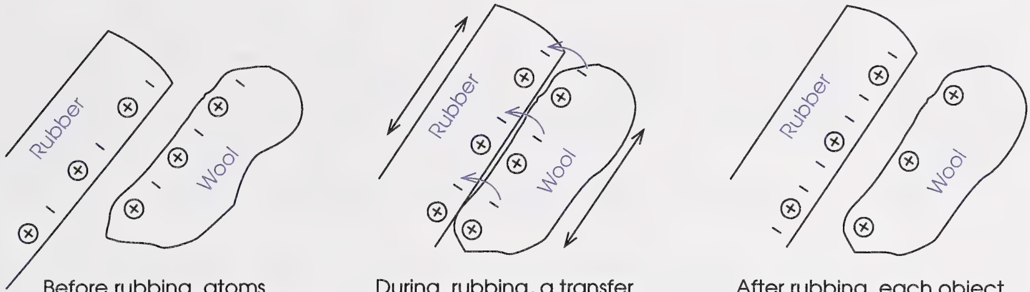
To investigate the modern theory that explains the cause of electrostatic charges, read A Microscopic View of Charge on page 410 of your textbook. Then answer the following questions.

1. The modern theory of electrostatic charges actually began in the early 1800s, when a chemist by the name of John Dalton suggested that all matter is composed of indivisible units of matter called atoms. These atoms seemed to be electric in nature. This electric nature was eventually assigned to tiny particles. Copy the following headings into your notebook and leave enough space under each heading for your answers. Complete the chart by retracing the discovery of the atom and its particles.

Date	Scientist	Part of Atom Discovered and Its Charge	Location of the Part of the Atom
1897			
1909–1911			

2. Why are atoms considered to be electrically neutral?

3. Study the following diagrams and use them to answer the questions.



Before rubbing, atoms of wool and rubber are electrically neutral.

During rubbing, a transfer of electrons occurs.

After rubbing, each object has gained a net charge.

law of conservation of charge – The total amount of charge in a closed system remains constant.

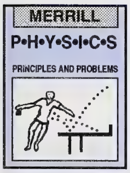
a. What is the purpose of rubbing objects in the formation of charged objects? Refer to the **law of conservation of charge** in your answer.

b. Which charged particle is transferred during rubbing?

ion – an atom that has gained or lost electrons, leaving it with a net negative or positive charge

c. Copy these headings into your notebook. Be careful to leave enough space for your answers.

Object	Indicate whether the object has lost or gained electrons.	Indicate the type of ion formed in the object.	Indicate the net charge on the object.
Rubber			
Wool/Fur			



d. Why can't the positive nuclei be transferred during the rubbing of solid objects?

Check your answers by turning to the Appendix, Section 1: Activity 2.

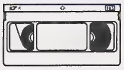
electric conductor – a material through which charge easily moves

electric insulator – a material through which charge does not easily move

Once an object attains a net charge, this charge may remain on the surface of the object or it may move freely within the object. How the electrons behave in the substance is used to classify all substances into two main categories: **electric conductors** and **electric insulators**. These terms are usually shortened to **conductors** and **insulators** when the context is known to be electricity. Read Conductors and Insulators on page 411 of your textbook to find out more about conductors and insulators.

4. What is the basic difference between an electric conductor and an electric insulator?

5. Explain the circumstances by which air can become a conductor, even though it is normally an insulator.



The video series *Electricity* contains a ten-minute program called *Conductors and Insulators*. Familiarize yourself with the following questions prior to watching the program. This will help you to focus on the main ideas while you are viewing. Note that you may have to periodically stop the tape in order to record your answers.

6. a. What type of force holds the electrons within an atom?

   b. Are all the electrons attracted to the nucleus with the same amount of force?

7. a. What is a conductor?

   b. Explain why certain electrons are able to move freely between neighbouring atoms in a conductor.

   c. Give three examples of substances that are good conductors.

8. a. What is an insulator?

   b. Explain why electrons are not able to move freely between neighbouring atoms in an insulator.

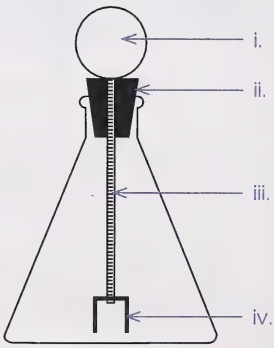
   c. Give three examples of substances that are good insulators.

The modern theory of electrostatics can explain why an object becomes charged and how this charge becomes distributed in a substance. Once the object is charged, it can be used to charge other objects using two different methods.

The video series *Electricity* contains a ten-minute program called *Charging by Conduction*. Familiarize yourself with the following questions prior to watching the program. This will help you to focus on the main ideas while you are viewing. Note that you may have to periodically stop the tape in order to record your answers.

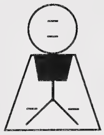
9. a. What is an electroscope?

   b. Name the parts shown in this diagram.



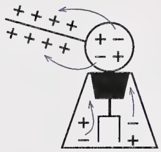
10. One method of using a charged object to charge another object is called **charging by conduction**. Sequences of events outlining this method are shown below in a **random order**.

I



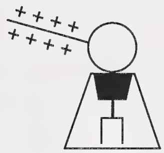
Rubber rod is removed and electroscope is charged negatively, causing leaves to repel and diverge.

II



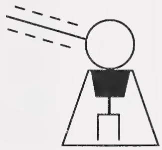
Free e$^-$ in the electroscope transfer to the positive glass rod.

III



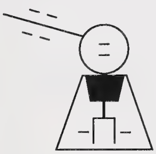
A positively charged glass rod is touched to the knob of a neutral electroscope.

IV



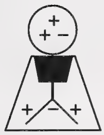
A negatively charged rubber rod is touched to the knob of a neutral electroscope.

V



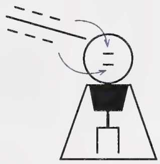
Free e$^-$ distribute evenly throughout the electroscope.

VI



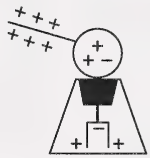
Glass rod is removed and electroscope is charged positive, causing leaves to repel and diverge.

VII



Free e$^-$ on the rubber rod transfer to the knob of the electroscope.

VIII



Free e$^-$ distribute evenly throughout the electroscope.

charging by conduction – the process of charging an object by bringing it into contact with a charged body

a. What is the proper sequence of events that will successfully charge the electroscope negatively by conduction? You will only need to use **four** of the eight steps shown.

b. What is the proper sequence of events that will successfully charge the electroscope positively by conduction? You will only need to use **four** of the eight steps shown.

c. If you are charging by conduction, how does the charge of the electroscope compare with the charge on the charging object?

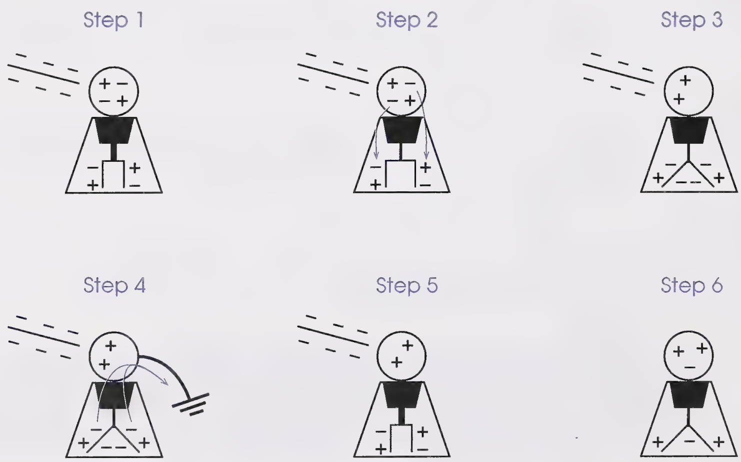
Check your answers by turning to the Appendix, Section 1: Activity 2.

Charging by conduction has some interesting and useful applications. The tires of a vehicle may become negatively charged through contact with the road. The parts of the metal body of the vehicle that are close to the tires can become positively charged because the electrons on these parts have been repelled by the negative charges on the tires. By the law of conservation of charge, other parts of the vehicle's body become negatively charged. The overall effect is that the sparks can jump between the parts of the vehicle that are oppositely charged. Large trucks that have a number of very large tires are particularly susceptible to this form of charging. This effect can be a serious hazard for the long tanker trucks that deliver gasoline to service stations. A single spark could ignite gasoline fumes while the truck is unloading its fuel. To help prevent this from happening, chains are dragged below the body of the truck to allow the charge that builds up to ground to the earth. The other safety precaution is that the operator of the truck usually grounds the body of the truck with a special grounding wire before transferring any fuel.

Another method of using a charged object to charge another object is called **charging by induction**. This method is shown in the video series *Electricity* on a program called *Charging and Discharging*. Familiarize yourself with the following questions prior to watching the program. This will help you focus on the main ideas while you are viewing. Note that you may have to periodically stop the tape in order to record your answers.

charging by induction – the process of charging an object by bringing it close to a charged body while the object is being grounded

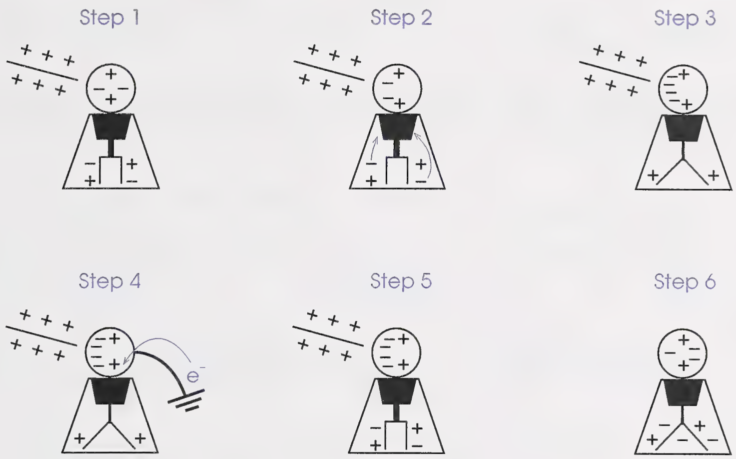
11. The following sequence of events shows the steps necessary to charge an electroscope by induction using a negatively charged object. Copy this series of diagrams into your notebook. Be sure to leave enough space under each diagram to describe what is happening in each step.



12. What does *grounding* an object mean?

13. Why is it necessary to remove the ground first and then move the charging rod in order to charge the electroscope?

14. The following sequence of events shows the steps necessary to charge an electroscope by induction using a positively charged object. Copy this series of diagrams into your notebook. Be sure to leave enough space under each diagram to describe what is happening in each step.



15. If you are charging by induction, how does the final charge of the electroscope compare with the charge on the charging object?

16. List two differences between charging an object by conduction and charging an object by induction.

Check your answers by turning to the Appendix, Section 1: Activity 2.

discharging – the process of losing charge and being neutralized

After an object becomes charged, the object may lose this net charge by **discharging**. The process of discharging may occur very slowly, where the excess charge slowly leaks away, or it may happen suddenly and may be observed as a spark.

Now think back to the question asked at the very beginning of this module. Is the spark that is observed while stroking a cat's fur similar to the very large spark seen in a bolt of lightning? The answer is yes. For further analysis of this question, do the following two questions.

17. When a person strokes a cat's fur, a spark is observed.

    a. Through what method of charging did the person and the cat's fur acquire a charge?

b. What type of charge did each acquire?

c. After each acquired a net charge, why didn't the charge dissipate through them to the ground?

d. As the person reaches to stroke the cat, a spark is observed. What is causing this spark?

18. As huge thunderclouds roll across the sky, a spectacular display of lightning may be observed.

a. Through what method of charging does the earth acquire a charge?

b. If the bottom of the cloud has too many electrons, describe the charge on the top and the bottom of the cloud.

c. If the bottom of the cloud discharges to the earth's surface (seen as a lightning bolt), what type of charge must have been induced on the earth's surface?

d. If lightning travels through the air as a bolt, this implies that the air is a conductor. What is the special name of this conductor?

e. A lightning bolt often never reaches the earth's surface. How is this discharge occurring?

Check your answers by turning to the Appendix, Section 1: Activity 2.

In Activity 2 you studied three methods of charging objects: friction, conduction, and induction. You were able to explain each using the modern theory of electrostatics.

Follow-up Activities

If you had difficulties understanding the concepts in the activities, it is recommended that you do the Extra Help. If you have a clear understanding of the concepts, it is recommended that you do the Enrichment.

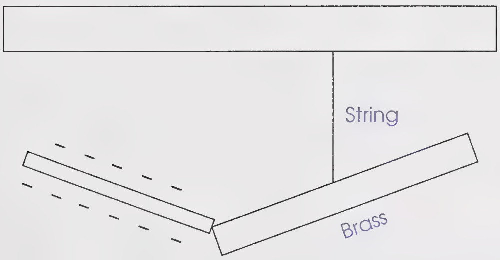
Extra Help

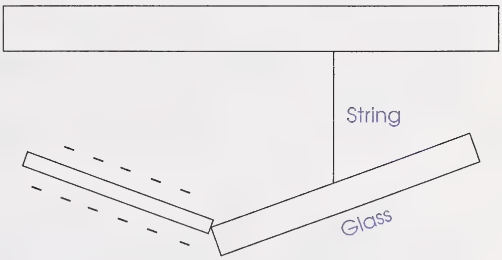
1. In Section 1 you studied various causes and effects of electrostatic charges. Match each effect described with its corresponding cause.

Effect	Cause
a. After a comb is rubbed through your hair, it picks up tiny pieces of paper.	i. Objects can obtain an electrostatic charge by conduction.
b. When a charged rod touches an electroscope, the leaves on the electroscope separate.	ii. Objects can obtain an electrostatic charge by induction.
c. When a charged rod is brought near an electroscope, the leaves on the electroscope separate.	iii. Objects can obtain an electrostatic charge by friction.

In Section 1 you also learned new terminology to describe electrostatic effects.

2. A brass metal rod and a glass rod are both suspended from the ceiling by insulating string, as shown in the following diagrams.

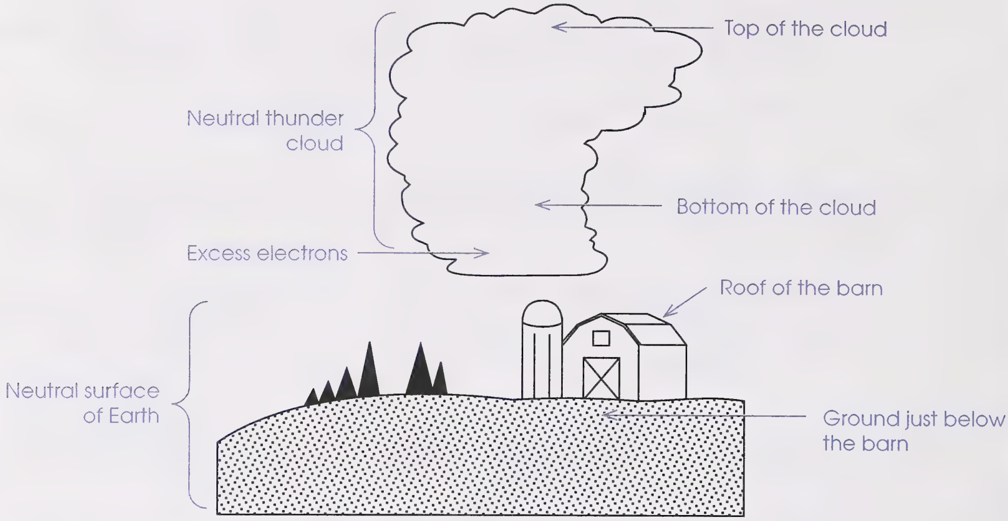




   a. Copy the diagrams into your notebook. Then compare the distributions of charge on the brass rod and glass rod by drawing the appropriate charges on each diagram.

   b. Explain the differences in the charge distributions of the glass rod and brass rod.

3. Study the following diagram and use it to answer the questions that follow.



a. Describe the charge on the top of the cloud.

b. Describe the charge on the bottom of the cloud.

c. Describe the charge on the roof of the barn.

d. Describe the charge in the ground just below the barn.

4. Refer to the previous diagram as you answer the parts of this question.

a. What law did you use to determine the charge on the top of the cloud? Explain concisely.

b. What is the name of the process by which the bottom of the cloud became charged?

c. What is the name of the process by which the roof of the barn became charged?

Check your answers by turning to the Appendix, Section 1: Extra Help.

Enrichment

Do **one** of the following questions.

1. You have observed that antistatic sheets remove **static cling** from clothes while they are being dried in a clothes dryer. How do antistatic sheets work?

2. If sugar is passed through a small opening and allowed to fall as a fine stream onto a piece of paper, the sugar will first accumulate in a small pile and then it will eventually begin to deflect and scatter all over the paper. Try doing this and then explain why it happens.

3. A fine stream of falling water can be attracted to both negatively and positively charged rods. Try doing this and then explain why it happens.

Check your answers by turning to the Appendix, Section 1: Enrichment.

Conclusion

In this section you were first introduced to some common electrostatic phenomena and then you studied the cause of these electrostatic charges. It is important to remember that the law of conservation of charge was not violated, since the charging of objects using any method simply involves the movement of electrons. Finally, you observed that electrostatic charges exert forces on each other. In Section 2 you will continue to study the forces between electrostatic charges.

Assignment Booklet

ASSIGNMENT

Turn to your Assignment Booklet and do the assignment for Section 1.

Section

2 Electrostatic Forces

THE BETTMANN ARCHIVE

In 1785 Charles Augustin de Coulomb experimentally verified a law which described electric forces. It is interesting to know that Henry Cavendish had actually discovered this law a full decade before Coulomb, but did not publish his results. Cavendish also differed from Coulomb in the techniques that he used to study electric forces.

Coulomb was a former military engineer, and so he was able to design and build a precision device to measure electric forces. This machine, called a torsion balance, was used by Coulomb to measure the electric forces between small, charged spheres. His data verified that the force between two charged objects obeyed a law very similar in form to Newton's law of gravitation.

Cavendish was a pure scientist who had a passion for discovering the truths of nature, but he had no talent for building delicate scientific instruments. Although Cavendish used a torsion balance (his was designed and built by another English scientist, Michell), his technique for measuring charge was unorthodox, to say the least. He let the charged objects discharge through his fingers and then used the degree of resulting pain to estimate the relative charge on the objects. It is amazing that Cavendish was able to reach the same conclusions as Coulomb using such unusual techniques!

You'll be glad to know that in this section you will be focusing on the techniques of Coulomb, not Cavendish! You will begin by examining Coulomb's procedure and then you will analyse sample data from a Coulomb-type experiment. The section ends with a problem-solving activity that will allow you to combine Coulomb's law with the techniques of vector analysis.

Activity 1: Introducing Coulomb's Technique

Coulomb did not begin his work on determining the electric force law on his own. As the following timeline indicates, much of the essential groundwork had already been done by other scientists.

Date	Scientist	Contribution to Coulomb's Work
1687	Isaac Newton	Published his great book *Mathematical Principles of Natural Philosophy*. This book included his three laws of motion and his law of universal gravitation $\left(F_g = \frac{Gm_1m_2}{r^2}\right)$.
1775	Benjamin Franklin	Franklin notices that a small cork inside a hollow, charged can experiences no force. The same cork experiences a force on the outside of the can. He writes to Joseph Priestley and asks him to repeat the experiment.
1776-1777	Joseph Priestley	Priestley verifies Franklin's results and realizes a connection to Newton's law of universal gravitation. In Newton's famous book, he showed mathematically that an object would experience no force of gravity inside a hollow planet. This was a consequence of the fact that the force of gravity varies as the inverse square of distance. Priestley instantly likened the cork to the object and the hollow can to the hollow planet. Priestley suggested that this indicated that the force of electricity could also be an inverse square law.

The essential starting point of Coulomb's work was the law of universal gravitation $\left(F_g = \frac{Gm_1m_2}{r^2}\right)$. The following questions will help you review the key features of this equation.

1. List all the variables that influence the magnitude of the force of gravity.

2. How does increasing the size of both masses influence the magnitude of the force of gravity?

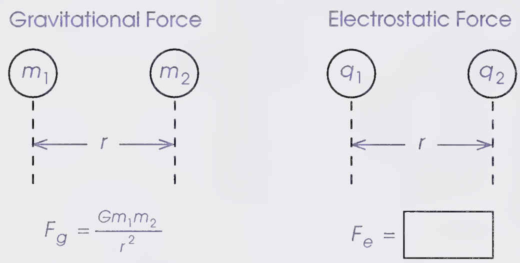
3. How can your answer to the previous question be expressed mathematically?

4. How does increasing the distance between the two masses influence the magnitude of the force of gravity?

5. How can your answer to the previous question be expressed mathematically?

Check your answers by turning to the Appendix, Section 2: Activity 1.

It should now be possible for you to use your knowledge of the law of universal gravitation and Priestley's suggestion to speculate about the nature of the electrostatic force.



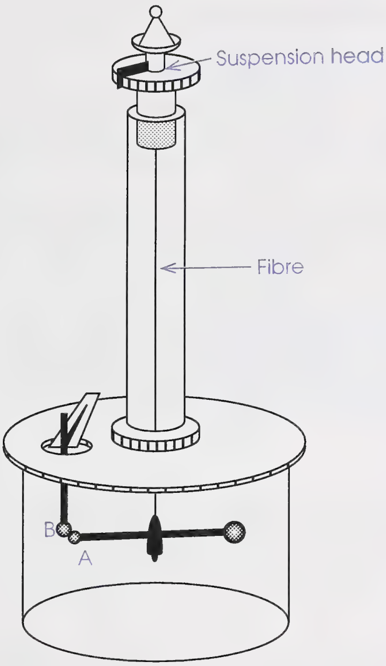
6. Which variables are likely to influence the magnitude of the electrostatic force?

7. How would increasing the size of both charges likely influence the magnitude of the electrostatic force?

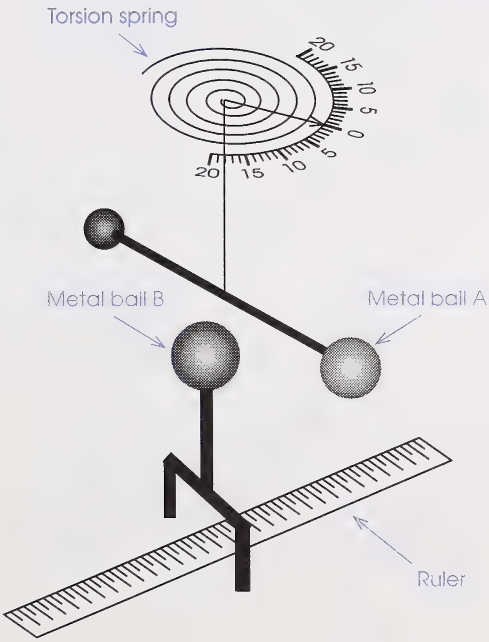
8. How would increasing the distance between the two charges likely influence the magnitude of the electrostatic force?

Check your answers by turning to the Appendix, Section 2: Activity 1.

Although the kind of thought used to answer the previous questions is very helpful as a starting point, it is important to verify these educated guesses with data collected from an experiment. Coulomb did this with his torsion balance, which is shown in the portrait reproduced in the introduction to this section. A detailed drawing of the torsion balance is shown in the following diagrams.



In Coulomb's torsion balance a horizontal, balanced rod is suspended by a thin, stiff fibre of silver wire. The wire twists when a force is exerted on ball A, which is shown at one end of the rod. The twisting of the wire can be measured at the suspension head at the top, which indicates the force acting on ball A.



A simplified schematic diagram of the torsion balance is shown to the left. This simplified version shows how the variables of distance of separation (r) and charge (q) could be used to measure the electrostatic force $\left(F_e\right)$.

In Activity 2 you will examine sample data from a torsion-balance experiment.

Activity 2: Investigating Coulomb's Law

In Activity 1 you probably hypothesized that $\vec{F}_e$ depends on the amount of charge on each object and the distance between the centres of the charges. These are the same hypotheses that Coulomb investigated while developing his law.

Science Skills

- ❒ A. Initiating
- ☑ B. Collecting
- ☑ C. Organizing
- ☑ D. Analysing
- ❒ E. Synthesizing
- ❒ F. Evaluating

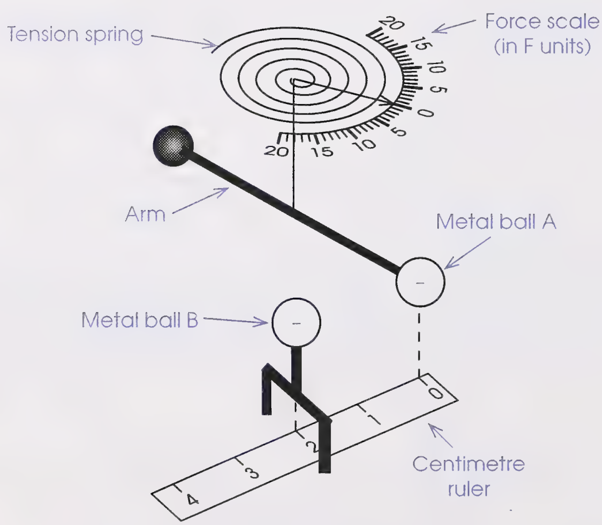
Investigation: The Effect of Distance on the Electrostatic Force

Purpose

In this investigation you will examine sample data from a torsion-balance experiment to determine the relationship between the distance of separation and the electrostatic force.

Materials

The only materials that you will need are the schematic torsion-balance diagrams that are provided for you.



Study the previous diagram and answer the following questions.

1. What type of force exists between ball A and ball B? Note that they are both metal and have similar charges.

2. Will the force be attractive or repulsive?

3. If ball B is in a fixed position and ball A is free to rotate, will ball A rotate clockwise or counterclockwise?

Check your answers by turning to the Appendix, Section 2: Activity 2.

If the arm on the torsion balance rotates, this causes the tension spring to tighten with a certain force, which is indicated on the scale. Coulomb had predetermined the graduation of the force scale in grains of force, but, in this simplified version, the scale is set in units of force that will be referred to as F units.

Procedure

- Ball B is initially charged negative by touching it to a charged rubber rod that has been rubbed with fur. Although Coulomb did not know how much charge was on ball B, he called the amount of charge on ball B q_B.

- Ball B is now touched momentarily to ball A, which was initially neutral.

4. What happens to ball A when it is in contact with ball B?

5. a. If balls A and B are identical, what is the total charge present on balls A and B?

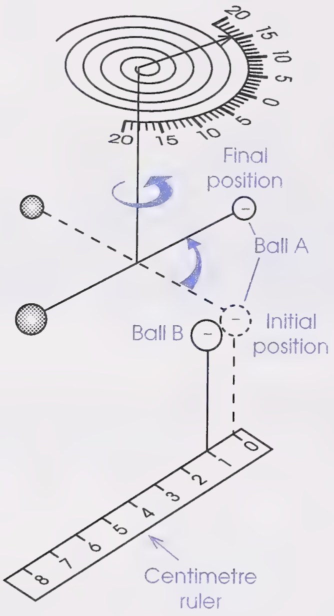
   b. What is the charge on each ball?

- With ball A held in place, ball B is now placed 1.0 cm away. Ball A is then released, allowing it to rotate.

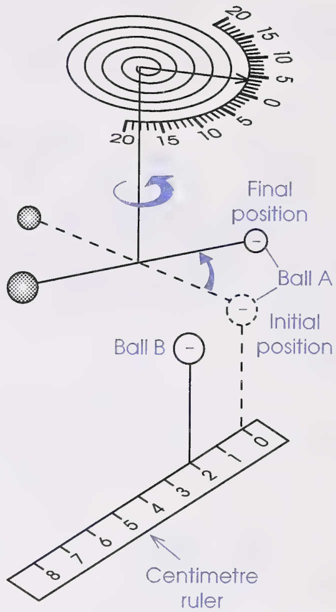
- The F_e repulsion is measured and the procedure is repeated with ball B set at positions 2.0 cm, 4.0 cm, and 8.0 cm. The results of each trial are indicated in the diagrams shown in the Observations section. Note that the angles of rotation have been made large enough for you to make force measurements. In Coulomb's actual apparatus, the angles of rotation were all less than 10°.

Observations

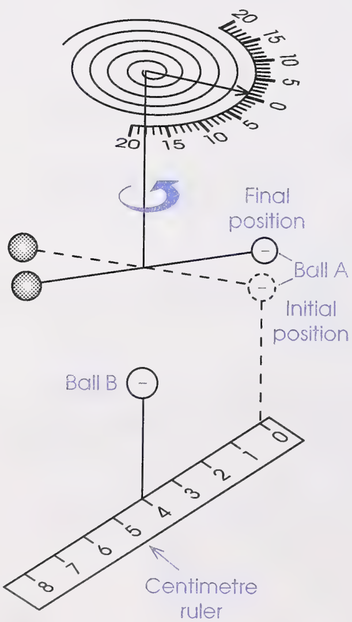
Trial 1:



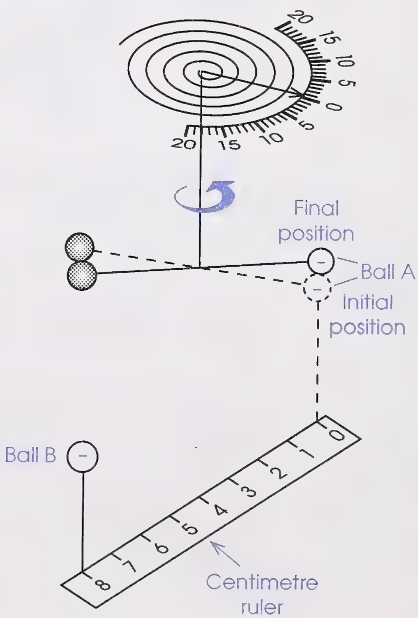
Trial 2:



Trial 3:



Trial 4:



Data

6. Study the diagrams and create a chart of values depicting the force of electrostatic repulsion (F_e) in F units when the distance between the charges (r) is 1.0 cm, 2.0 cm, 4.0 cm, and 8.0 cm.

Check your answers by turning to the Appendix, Section 2: Activity 2.

Analysis

7. Draw a graph of F_e versus r. Use the standard graph paper with 1-cm squares. Be sure to leave eight squares on the horizontal axis and ten squares on the vertical axis.

8. Describe the shape of the graph drawn in the previous question.

9. The graph of the data needs to be straightened.

   a. Using Priestley's idea, how could you manipulate the data to get a straight-line graph?

   b. Create a new chart with columns for the distance (r), the new values that you will be plotting, and the electrostatic force (F_e).

   c. Draw the straight-line graph from the manipulated data. Use the standard graph paper with 1-cm squares. Be sure to leave ten squares on the horizontal axis and eight squares on the vertical axis.

Conclusions

10. Based on your results, write a mathematical expression describing the relationship between F_e and r. What is this type of relationship called?

11. How does this expression compare with Newton's relationship between F_g and r?

Check your answers by turning to the Appendix, Section 2: Activity 2.

The previous investigation indicates that Priestley's hunch was right and it also sheds light on some of the behaviour between charged objects that you observed in Section 1.

Why are the repulsive forces between two charged pieces of tape most intense when the pieces are very close together? The inverse-square nature of the electrostatic force provides the answer. If the two charged pieces of tape are only 2 cm apart, they may experience an electrostatic force that you could call F_e. Taking these two pieces of tape and moving them 4 cm apart means that the force is now only $\frac{1}{4}F_e$. Multiplying the distance by 2 has the effect of reducing the force by $\frac{1}{4}$ because the inverse of 2^2 is $\frac{1}{4}$. Using this same line of reasoning, you can show that making the distance four times greater would reduce the force by $\frac{1}{16}$, and that making the distance ten times greater would reduce the force by $\frac{1}{100}$.

In the next investigation you will find out if the charges in Coulomb's law have the same effect on force as the masses in Newton's law of universal gravitation.

Investigation: The Effect of Charge on Electrostatic Force

Purpose

In this investigation you will analyse data collected from a torsion-balance experiment to determine how varying the charge on one ball can influence the electrostatic force between the two balls.

Materials

The only material needed is sample data from a torsion balance-type experiment. This data is provided for you in the investigation.

Background Information

Although Coulomb had no way of determining the exact amount of charge on an object, he did devise an ingenious method of varying the charge in a controlled way.

MERRILL P•H•Y•S•I•C•S PRINCIPLES AND PROBLEMS

Read pages 415 and 416 of your textbook and answer the following questions.

12. If Coulomb first charged ball B by touching it to a charged rubber rod, the amount of charge on ball B could be called q. If ball B is now touched momentarily to ball A, which is identical to ball B, how much charge does each ball now hold? Assume that ball A was initially neutral.

13. How did Coulomb propose to vary the charge by using another ball, ball C, which is identical to the others and neutral?

Procedure

By varying the charge on ball B and placing it a known distance from ball A each time, Coulomb measured the force of repulsion between the two balls by reading the force scale. The following table summarizes his results.

Data

Charge on Ball A (q_A) (q units)	Charge on Ball B (q_B) (q units)	Product of Charges $(q_A q_B)$ $(q^2 \text{ units})$	Force of Repulsion (F_e) (F units)
$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{4} = 0.25$	4
$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{8} = 0.125$	2
$\frac{1}{2}$	$\frac{1}{8}$	$\frac{1}{16} = 0.0625$	1
$\frac{1}{2}$	$\frac{1}{16}$	$\frac{1}{32} = 0.0313$	$\frac{1}{2}$

Analysis

14. Plot a graph of electrostatic force (F_e) versus the product of the two charges $(q_A q_B)$. Use the standard graph paper with 1-cm squares. Be sure to leave six squares on the horizontal axis and ten squares on the vertical axis.

Conclusions

15. Describe the shape of the graph you plotted.

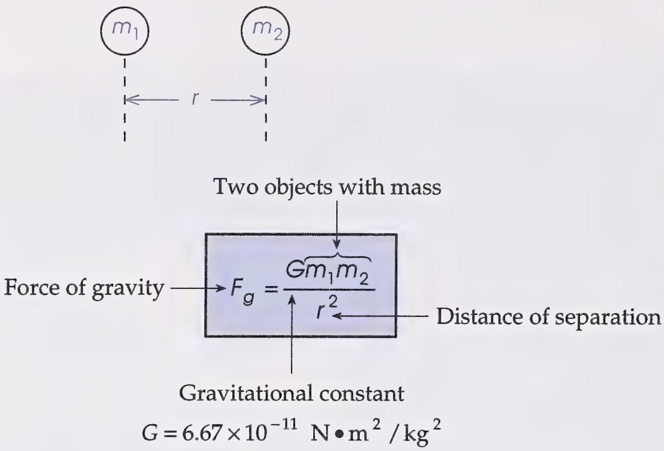
16. Based on the graph, what is the relationship between the electrostatic force and the product of the charges?

Check your answers by turning to the Appendix, Section 2: Activity 2.

In this activity you have been using data and techniques similar to those used by Coulomb to determine the equation for electrostatic force. The similarities between the equations for gravitational force and electrostatic force can now be clearly illustrated.

17. Complete the following comparison chart by copying it into your notebook and then filling in the missing information. The constants can be found on the front page of the Physics 30 data sheets.

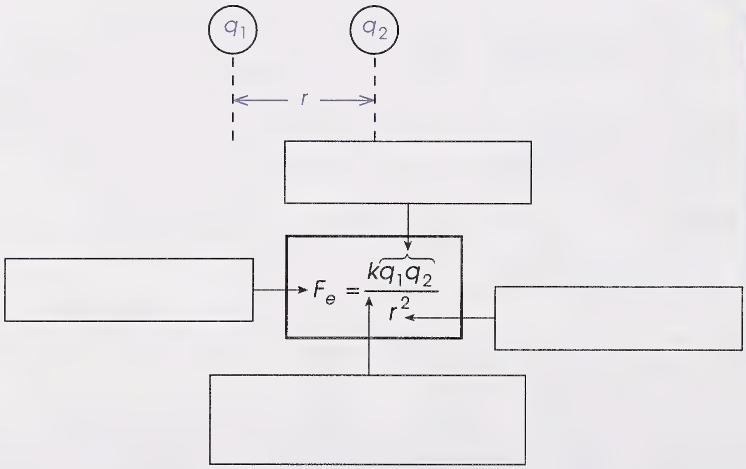
The Law of Universal Gravitation



Quantity	Units
F_g	N
G	$\frac{\mathrm{N \bullet m^2}}{\mathrm{kg^2}}$
m	kg
r	m

Coulomb's law – the law which describes the electrostatic force between two charged objects

Coulomb's Law



Quantity	Units
F_e	
k	
q	C
r	

coulomb (C) – the unit of charge in the SI system

In honour of the pioneering work done by Coulomb, the equation describing electrostatic force is named Coulomb's law and the unit of charge in the SI system is the **coulomb (C)**. The coulomb is a huge unit of charge. One coulomb is the charge of 6.25×10^{18} electrons. In common terms, a coulomb is the amount of charge delivered by a typical lightning bolt. It is because the coulomb is such a tremendously large amount of charge that the coulomb constant is so large.

18. Imagine the following situation. Two metal globes have both been given a charge of +1.00 C and are separated by 1.00 m.

    a. Calculate the magnitude of the electrostatic force of repulsion between the two globes using Coulomb's law.

    b. Why must this situation only be imagined? Why couldn't you set this up in the laboratory?

Check your answers by turning to the Appendix, Section 2: Activity 2.

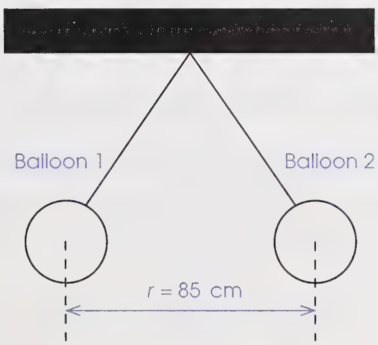
It is truly remarkable that two of the most fundamental laws in physics, which describe completely different phenomena and are based on completely different observations, should be so similar. The reason for these similarities remains a mystery to this day. However, it would be wrong to say that these forces are identical because there are some important differences:

- The force of gravity is always an attractive force.

- The electrostatic force can be attractive or repulsive, depending on the sign of the charges.

When solving problems with Coulomb's law, it is important to remember that the signs of the charges tell you about the direction of the electrostatic force, while the magnitude of the charges are substituted directly into the equation to help determine the magnitude of the force. The following example illustrates the recommended problem-solving technique for Physics 30.

Example



Two spherical balloons are estimated to each have a negative charge of 0.3 μC. If the balloons have their centres separated by 85 cm, calculate the magnitude and direction of the electrostatic force between them.

Solution

$$
\begin{aligned}
q_1 &= 0.3\ \mu\text{C} \\
&= 0.3 \times 10^{-6}\ \text{C} \\
&= 3 \times 10^{-7}\ \text{C} \\
q_2 &= 3 \times 10^{-7}\ \text{C} \\
r &= 85\ \text{cm} \\
&= 0.85\ \text{m} \\
F_e &= ?
\end{aligned}
$$

$$
\begin{aligned}
F_e &= \frac{kq_1q_2}{r^2} \\
&= \frac{\left(8.99 \times 10^9\ \text{N}\bullet\text{m}^2/\text{C}^2\right)\left(3 \times 10^{-7}\ \text{C}\right)\left(3 \times 10^{-7}\ \text{C}\right)}{(0.85\ \text{m})^2} \\
&= 1 \times 10^{-3}\ \text{N} \\
\vec{F}_e &= 1 \times 10^{-3}\ \text{N, repelling}
\end{aligned}
$$

This equation is a scalar equation. The signs of charges are not substituted into the equation.

The vector nature of the force is stated at the end of the problem. Since the balloons are both negative, they repel each other.

19. How would you describe the magnitude and direction of the electrostatic force on balloon 1?

20. How would you describe the magnitude and direction of the electrostatic force on balloon 2?

21. Which of Newton's laws is illustrated in your answer to the previous two questions? Explain concisely.

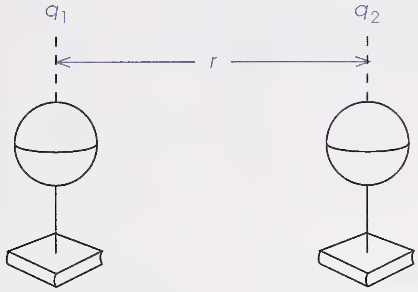
Check your answers by turning to the Appendix, Section 2: Activity 2.

In the next activity you will see how Coulomb's law can be applied to a variety of situations.

Activity 3: Applying Coulomb's Law

In Modules 1 and 2 you learned how to apply the laws of conservation of momentum and energy. In both cases it was essential to know the limitation of the laws so that you could use them properly. Without a closed, isolated system these laws could not be applied.

Limitations are also imposed by Coulomb's law. Most of these limitations can be best understood if you recall the conditions of Coulomb's basic experiment.



- It must be possible to accurately determine the distance of separation, r. The measurement of r may seem trivial at first, but if the object has an unusual shape and the charge is not distributed evenly over its surface, it can be very difficult to locate the centre of the entire charge distribution. If the object is spherical and has the charge distributed evenly, the charge can be treated as if it is all concentrated at the centre. The ideal circumstance is for the size of the object to be very small compared to r. Then the charge can be treated like a **point charge**.

point charge – an idealized charge that is so small that it takes up no space

The other limitations imposed by Coulomb's law relate to your work with vectors in the previous module:

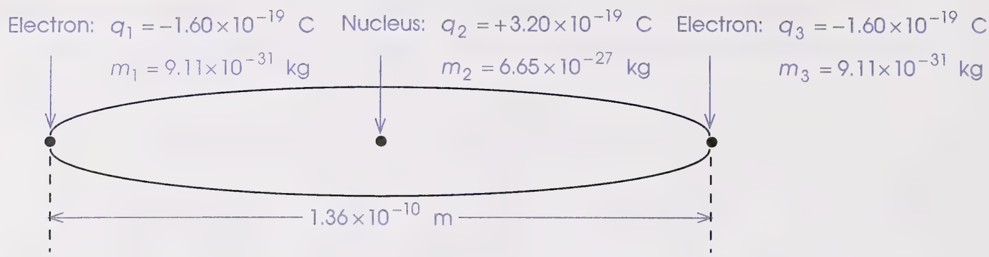
- It is crucial that you treat the equations as scalars and use the signs of the charges only to tell the direction of the force. If you substitute negatives into the equation (unfortunately, the textbook does this), the work with the x- and y-components of electrostatic force vectors becomes terribly confusing.

- The directions of the forces should always be related to a sign convention stated at the beginning of the solution.

Keep these ideas in mind as you work through the following example.

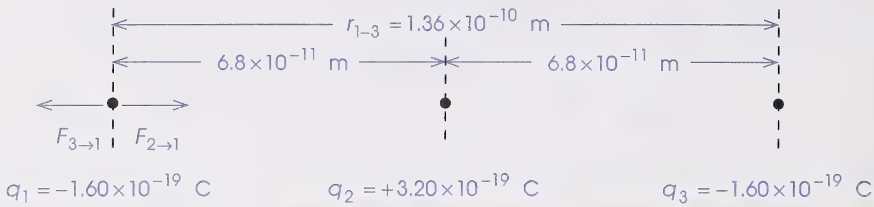
Example

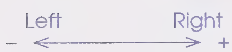
The following simplified diagram shows two electrons on opposite sides of the nucleus of a helium atom. Consider the nucleus to be in the middle of the two electrons. Determine the net force acting on the first electron (q_1) due to the nucleus (q_2) and the other electron (q_3). The diagram for this is shown on the next page.



Solution

Step 1: Redraw the diagram and show all the relevant data.





The directions of the forces acting on q_1 and a sign convention have been added. $F_{3\to1}$ means the force of q_3 acting on q_1.

Step 2: Apply Newton's laws to find the magnitude of $\vec{F}_{net}$.

$$\vec{F}_{net} = \vec{F}_{3\to1} + \vec{F}_{2\to1}$$

$$\left|\vec{F}_{net}\right| = -\left|\vec{F}_{3\to1}\right| + \left|\vec{F}_{2\to1}\right|$$

$$= \frac{-kq_3q_1}{(r_{1-3})^2} + \frac{kq_2q_1}{(r_{1-2})^2}$$

$$= \frac{-\left(8.99 \times 10^{9}\ \text{N}\bullet\text{m}^2/\text{C}^2\right)\left(1.60 \times 10^{-19}\ \text{C}\right)\left(1.60 \times 10^{-19}\ \text{C}\right)}{\left(1.36 \times 10^{-10}\ \text{m}\right)^2} + \frac{\left(8.99 \times 10^{9}\ \text{N}\bullet\text{m}^2/\text{C}^2\right)\left(3.20 \times 10^{-19}\ \text{C}\right)\left(1.60 \times 10^{-19}\ \text{C}\right)}{\left(6.8 \times 10^{-11}\ \text{m}\right)^2}$$

$$= \left(-1.244 \times 10^{-8}\ \text{N}\right) + \left(9.954 \times 10^{-8}\ \text{N}\right)$$

$$= 8.7 \times 10^{-8}\ \text{N}$$

The negative sign in front of $\left|\vec{F}_{3\to1}\right|$ indicates that this force is directed to the left, while the other force is directed to the right.

Step 3: Assess the direction of $\vec{F}_{net}$ and state the final answer.

$$\begin{aligned}\vec{F}_{net} &= +8.7\times10^{-8}\ \text{N}\\ &= 8.7\times10^{-8}\ \text{N, right}\end{aligned}$$

According to the sign convention, positive vectors are directed to the right.

This question provides an interesting example of the proper use of significant digits. Although this at first appears to be a three significant digit problem, the radius becomes a two significant digit measurement when the radius is determined from the circumference. This makes sense because the two radii measurements should add to give the circumference with the original three significant digits.

This example also illustrates how important it is to begin the solution with a diagram that includes a sign convention. You will be able to practise these techniques in the next two questions.

MERRILL P•H•Y•S•I•C•S PRINCIPLES AND PROBLEMS

1. Do Problem 8 on page 423 of your textbook.

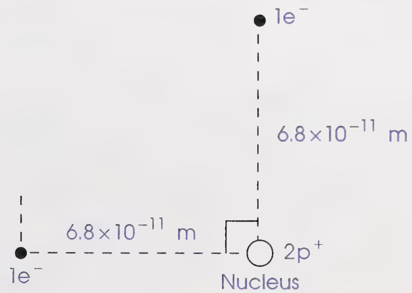
2. Do Problem 15 on page 423 of your textbook.

Check your answers by turning to the Appendix, Section 2: Activity 3.

As the following example indicates, the case of two charges acting on another charge does not necessarily mean that the three charges are in a line. The charges could also form a right angle.

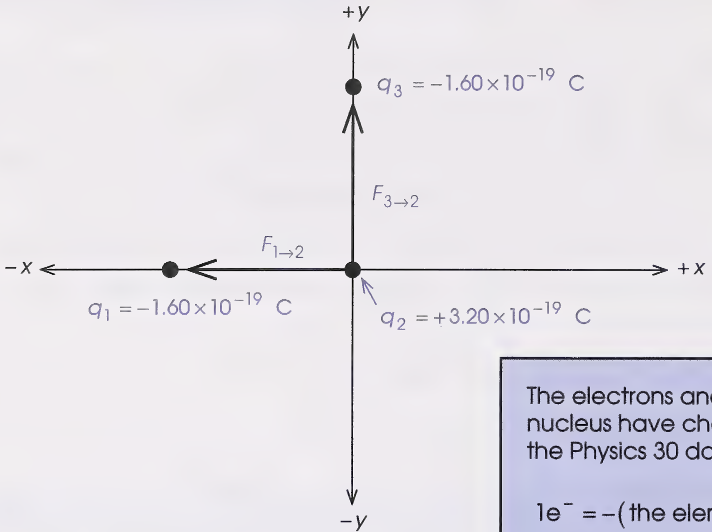
Example

The following simplified diagram shows two electrons outside the nucleus of a helium atom. Find the net force on the nucleus due to the two electrons.



Solution

Step 1: Redraw the diagram with point charges and show all the relevant data and an x-y axis drawn through the nucleus.



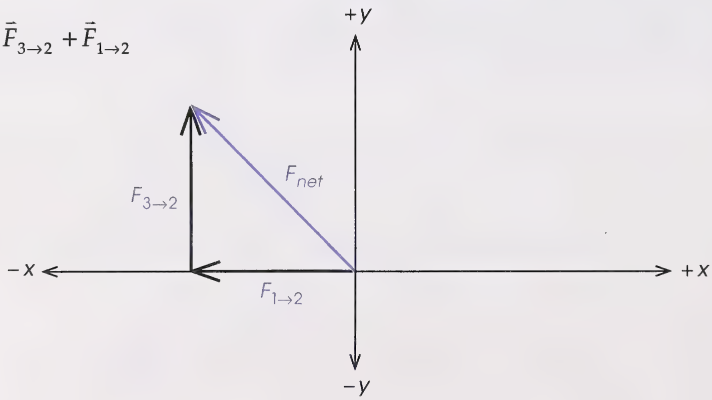
The electrons and the protons in the nucleus have charges that are given in the Physics 30 data sheets.

$$1e^- = -(\text{the elementary charge})$$
$$= -1.60 \times 10^{-19}\ \text{C}$$

$$2p^+ = +2(\text{the elementary charge})$$
$$= +2(1.60 \times 10^{-19}\ \text{C})$$
$$= +3.20 \times 10^{-19}\ \text{C}$$

Step 2: Apply Newton's laws and draw a vector diagram to determine $\vec{F}_{net}$.

$$\vec{F}_{net} = \vec{F}_{3 \rightarrow 2} + \vec{F}_{1 \rightarrow 2}$$



Step 3: Find the magnitude of the net force.

$$C^2 = A^2 + B^2$$

$$\left|\vec{F}_{net}\right|^2 = \left|\vec{F}_{3\to2}\right|^2 + \left|\vec{F}_{1\to2}\right|^2$$

$$= \left(\frac{(8.99\times10^9\ \mathrm{N\bullet m^2/C^2})(1.60\times10^{-19}\ \mathrm{C})(3.20\times10^{-19}\ \mathrm{C})}{(6.8\times10^{-11}\ \mathrm{m})^2}\right)^2 +$$

$$\left(\frac{(8.99\times10^9\ \mathrm{N\bullet m^2/C^2})(1.60\times10^{-19}\ \mathrm{C})(3.20\times10^{-19}\ \mathrm{C})}{(6.8\times10^{-11}\ \mathrm{m})^2}\right)^2$$

$$= (9.954\times10^{-8}\ \mathrm{N})^2 + (9.954\times10^{-8}\ \mathrm{N})^2$$

$$= (9.91\times10^{-15}\ \mathrm{N^2}) + (9.91\times10^{-15}\ \mathrm{N^2})$$

$$= 1.98\times10^{-14}\ \mathrm{N^2}$$

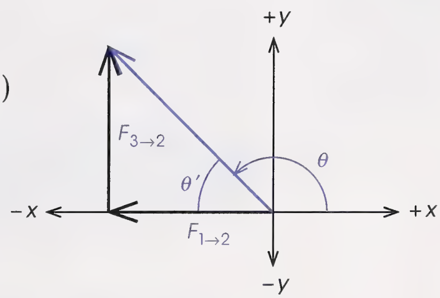
$$\left|\vec{F}_{net}\right| = 1.4\times10^{-7}\ \mathrm{N}$$

Step 4: Find the direction of the net force.

$$\tan\theta' = \frac{F_{3\to2}}{F_{1\to2}} = \frac{9.954\times10^{-8}\ \mathrm{N}}{9.954\times10^{-8}\ \mathrm{N}} = 1.000$$

$$\theta' = 45^\circ$$

$$\theta = 180^\circ - \theta' = 180^\circ - (45^\circ) = 135^\circ$$



Step 5: State the final answer.

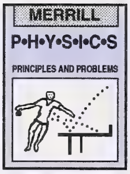
$$\vec{F}_{net} = 1.4\times10^{-7}\ \mathrm{N},\ 135^\circ$$

This example clearly shows how powerful a systematic approach to problem solving can be. You should have recognized that this method of dealing with vectors by using an *x-y* axis stems directly from your work in Module 2. Even though the topic is no longer momentum, the same strategies and techniques work once again. This is no stroke of luck – it is by design. Remember that the whole idea is to use the same overall strategies throughout the course so that you can be a successful problem solver. The topic may be different, but the same vector analysis techniques can be applied.

The following list summarizes the recommended approach that was illustrated in the previous example:

- The nucleus was the object that the forces acted on, so the x-y axis is drawn with its origin at the location of the nucleus.
- Be very careful to use a consistent, simple notation to keep track of forces.
- Always measure angles counterclockwise from the x-axis. This is the system that the sine and cosine functions on your calculator are designed to use, so it will make more challenging problems easier.
- Use the values stated on the Physics 30 data sheets for the charges on protons and electrons. Note that a helium nucleus is also known as an alpha particle and that its mass and charge are also given on the data sheets.
- Remember that trigonometric functions and the Pythagorean theorem deal only with the magnitudes of vectors. Use either absolute value signs or drop the vector arrow above the symbols to clearly communicate the idea that these are magnitude-only calculations.

Use the techniques outlined in the previous example to solve the following questions.



3. Solve the Example Problem on page 419 of your textbook.

4. Solve Problem 18.c. on page 423 of your textbook. Rather than solving Problems 18.a. and b. first, use the technique shown in the previous example. Note that you will have to rotate the x-y axis after the initial setup in order to solve the problem.

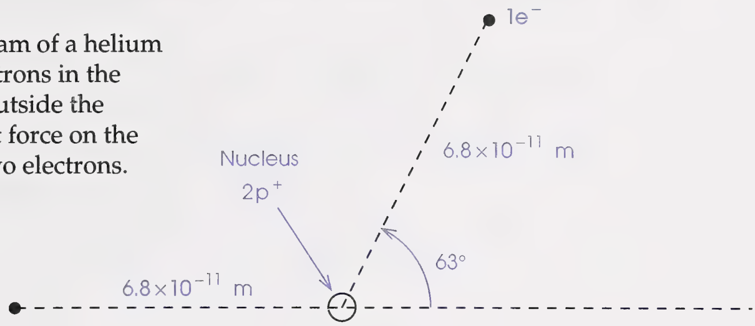
Check your answers by turning to the Appendix, Section 2: Activity 3.

As long as you take your time and consistently follow the recommended approach, even the most complicated problems can be solved. The key is to carefully draw the initial vector diagrams and to try not to squeeze the whole solution into a small space in your notebook.

The following example represents the most complicated type of Coulomb's law problem.

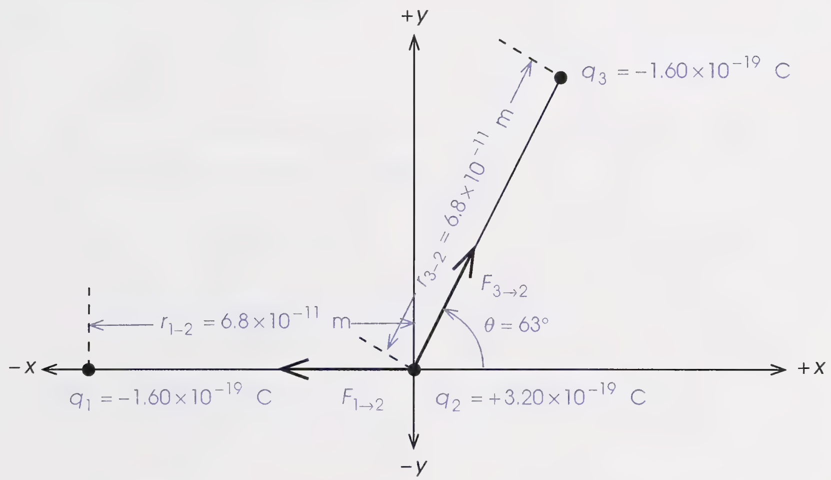
Example

This simplified diagram of a helium atom shows two electrons in the positions indicated outside the nucleus. Find the net force on the nucleus due to the two electrons.



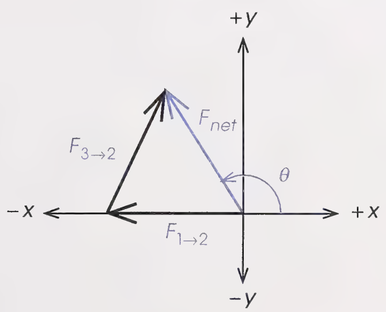
Solution

Step 1: Redraw the diagram with point charges and show all the relevant data and an *x*-*y* axis drawn through the nucleus.



Step 2: Find the net force and draw a vector diagram to determine $\vec{F}_{net}$.

$$\vec{F}_{net} = \vec{F}_{1\to 2} + \vec{F}_{3\to 2}$$

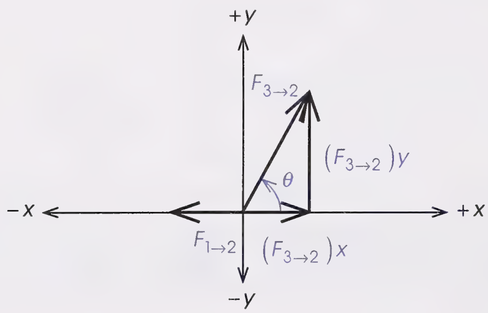


Step 3: Find the magnitudes of the forces.

$$\left|\vec{F}_{1\to 2}\right| = \frac{kq_1q_2}{\left(r_{1-2}\right)^2}$$
$$= \frac{\left(8.99\times 10^{9}\ \text{N}\bullet\text{m}^2/\text{C}^2\right)\left(1.6\times 10^{-19}\ \text{C}\right)\left(3.2\times 10^{-19}\ \text{C}\right)}{\left(6.8\times 10^{-11}\ \text{m}\right)^2}$$
$$= 9.954\times 10^{-8}\ \text{N}$$

$$\left|\vec{F}_{3\to 2}\right| = \frac{kq_3q_2}{\left(r_{3-2}\right)^2}$$
$$= \frac{\left(8.99\times 10^{9}\ \text{N}\bullet\text{m}^2/\text{C}^2\right)\left(1.6\times 10^{-19}\ \text{C}\right)\left(3.2\times 10^{-19}\ \text{C}\right)}{\left(6.8\times 10^{-11}\ \text{m}\right)^2}$$
$$= 9.954\times 10^{-8}\ \text{N}$$

Step 4: Find the *x*- and *y*-components of the forces.



$$\left|\vec{F}_{1\to 2}\right| = 9.954\times 10^{-8}\ \text{N}$$
$$\left|\vec{F}_{1\to 2}\right|_x = -9.954\times 10^{-8}\ \text{N}$$
$$\left|\vec{F}_{1\to 2}\right|_y = 0\ \text{N}$$

$$\left|\vec{F}_{3\to 2}\right| = 9.954\times 10^{-8}\ \text{N}$$
$$\left|\vec{F}_{3\to 2}\right|_x = \left(9.954\times 10^{-8}\ \text{N}\right)\left(\cos 63°\right)$$
$$= 4.519\times 10^{-8}\ \text{N}$$
$$\left|\vec{F}_{3\to 2}\right|_y = \left(9.954\times 10^{-8}\ \text{N}\right)\left(\sin 63°\right)$$
$$= 8.869\times 10^{-8}\ \text{N}$$

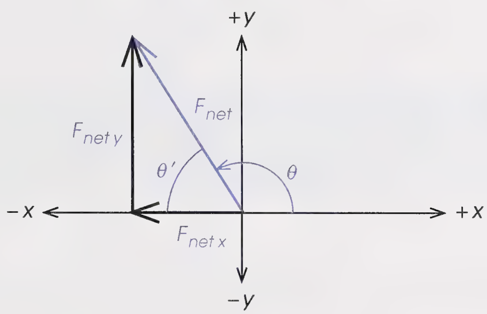
Step 5: Find the magnitude of the resultant.

$$\left|\vec{F}_{net}\right|_x = \left(-9.954\times10^{-8}\ \text{N}\right)+\left(4.519\times10^{-8}\ \text{N}\right)$$
$$= -5.435\times10^{-8}\ \text{N}$$

$$\left|\vec{F}_{net}\right|_y = (0)+\left(8.869\times10^{-8}\ \text{N}\right)$$
$$= 8.869\times10^{-8}\ \text{N}$$

$$C^2 = A^2 + B^2$$
$$\left|\vec{F}_{net}\right|^2 = \left|\vec{F}_{net}\right|_x^2 + \left|\vec{F}_{net}\right|_y^2$$
$$= \left(-5.435\times10^{-8}\ \text{N}\right)^2 + \left(8.869\times10^{-8}\ \text{N}\right)^2$$
$$= \left(2.954\times10^{-15}\ \text{N}^2\right)+\left(7.866\times10^{-15}\ \text{N}^2\right)$$
$$= 1.082\times10^{-14}\ \text{N}^2$$
$$= 1.0\times10^{-7}\ \text{N}$$

Step 6: Calculate the direction of the net force.



$$\tan\theta' = \frac{F_{net\,y}}{F_{net\,x}}$$
$$= \frac{8.869\times10^{-8}\ \text{N}}{5.435\times10^{-8}\ \text{N}}$$
$$\theta' = 58.5°$$

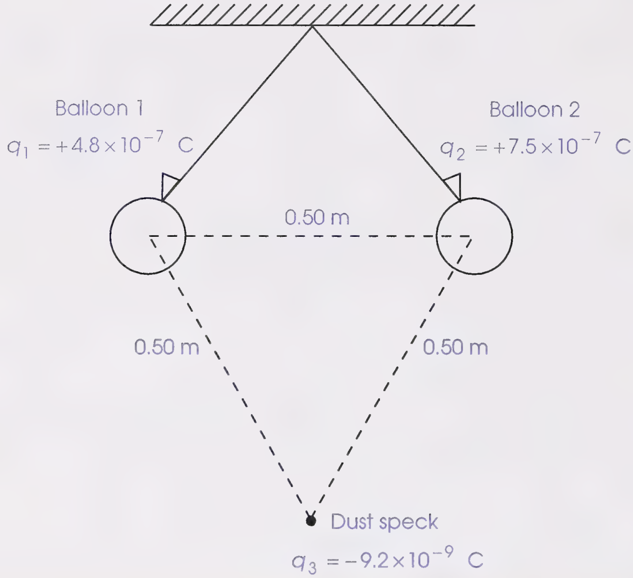
$$\theta = 180° - \theta'$$
$$= 180° - 58.5°$$
$$= 121.5°$$
$$= 122°$$

Step 7: State the final answer.

$$\vec{F}_{net} = 1.0\times10^{-7}\ \text{N},\ 122°$$

Once again, you can see how a complex problem can be solved with a methodical, systematic approach. Try these techniques as you do the next question.

5. The following diagram shows two charged spherical balloons suspended from a ceiling. The balloons have their centres separated by 0.50 m. A charged dust speck drifts into a position that is exactly 0.50 m from each balloon. Calculate the net force on the dust speck.



Check your answers by turning to the Appendix, Section 2: Activity 3.

In this activity you were able to calculate the $\vec{F}_{e\ net}$ in four situations:

- two charges in a straight line
- three charges in a straight line
- three charges at a right angle
- three charges at an obtuse angle

Of course, there are other more complicated situations, but Physics 30 will only concentrate on these types of situations.

Follow-up Activities

If you had difficulties understanding the concepts in the activities, it is recommended that you do the Extra Help. If you have a clear understanding of the concepts, it is recommended that you do the Enrichment.

Extra Help

1. You studied two types of forces in Section 2 $\left(\vec{F}_g \text{ and } \vec{F}_e\right)$. These forces have similarities and differences. Copy the following headings into your notebook. Be careful to leave enough space under each heading to record your answers. Complete the chart by listing three similarities and three differences.

Comparing $\vec{F}_e$ and $\vec{F}_g$	
Similarities	**Differences**

2. You learned that the unit of charge is 1 C. How many electrons are there in 4.50 C if $1\ \text{C} = 6.45 \times 10^{18}$ electrons?

3. Determine the electrostatic force between two charges, $q_A = +5.00 \times 10^{-6}$ C and $q_B = +1.00 \times 10^{-6}$ C, if they are placed 10.0 cm apart.

4. In Activity 3 of this section you combined your knowledge of vectors with the equation for Coulomb's law. The following questions relate to the examples that were presented and the problems that you solved in Activity 3.

   a. If three charges are in a line, and you are asked to calculate the electrostatic force on one of these charges, how do you indicate direction on the vector diagram?

   b. If three charges, A, B, and C, are not in a line, and you are asked to find the net force on C, where do you place the origin of the *x*-*y* axis in your solution?

   c. If three charges, A, B, and C, form an angle other than 90°, and you are asked to find the net force on C, what should you do **after** you calculate $F_{B \to C}$ and $F_{A \to C}$?

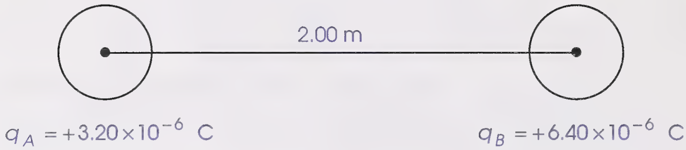
Check your answers by turning to the Appendix, Section 2: Extra Help.

Enrichment

Do **one** of the following questions.

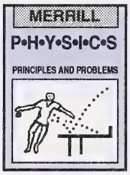
1. Problem Solving

   The following diagram shows two charges in a line.



   Where should a third charge, $q_C = +1.00 \times 10^{-6}$ C, be placed so that it will experience a net electrostatic force of 0 N?

2. Reviewing Concepts



   Use diagrams to help answer Concept Review questions 2.1, 2.2, 2.3, and 2.4 at the bottom of page 420 in your textbook.

Check your answers by turning to the Appendix, Section 2: Enrichment.

Conclusion

In this section you first studied how Cavendish and Coulomb studied the force due to electrostatic charges, $\vec{F}_e$, and then you investigated how the equation for calculating the electrostatic force, known as Coulomb's law, was developed. Finally, you mathematically calculated $\vec{F}_e$ in various situations. In the next section you will study how the effect of electrostatic charges developed into a field theory necessary to describe many other phenomena in physics.

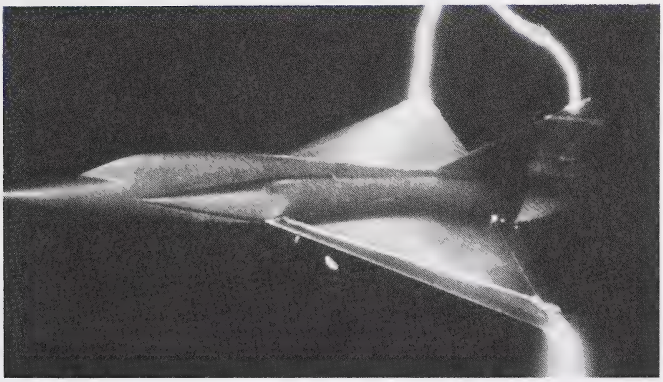
Assignment Booklet

ASSIGNMENT

Turn to your Assignment Booklet and do the assignment for Section 2.

Section

3 Electric Fields



NASA

Lightning is a wonderfully mysterious phenomenon. Although some aspects of its nature are well understood, other characteristics remain unexplained.

This photograph shows a research experiment undertaken by NASA to study the effects of multiple lightning strikes on scale models of newly designed aircraft.

Lightning strikes airplanes all the time, with very little damage ever inflicted on the planes.

Lightning strikes to human beings are another matter altogether. The outcome of a person being hit by lightning seems to depend very much on the circumstances of the particular strike. Some people have been struck by lightning several times and seem to have suffered no long-term health problems. In some cases, if a person's skin is quite wet, the excess charge delivered by the lightning travels down the outside of this water layer and does not enter the body, leaving the person unharmed. The only negative effect in many of these cases seems to be disorientation because the rapid evaporation and expansion of the moisture on the skin can blow the clothes and shoes right off the body! Of course, if the charges penetrate the body, the effects can be very serious. Even a mild electric shock can cause heart failure, while large surges of charge can cause fatal internal burns.

Lightning is just one example of a range of phenomena that can be explained quite effectively using the concept of an electric field.

In this section you will explore the historical development of the theory of electric fields. Then you will investigate how electric fields can be described mathematically and diagrammatically. Finally, you will analyse how an electric field can interact with other charged particles in a variety of situations.

Activity 1: Explaining Action at a Distance

Wouldn't you be surprised if the television you were watching suddenly jumped up and moved around? Your faith in the laws of physics would be shattered! The absurdity of this situation occurring is similar to the circumstances involving the introduction of the field concept in physics.

field – a region of influence surrounding an object that can exert a force on another object

Your previous studies in Physics 20 introduced you to the idea that if one object exerts a force on a second object, the second object accelerates. Upon closer examination you also observed that this can only occur if one object actually makes **contact** with the other object. Most of your everyday experiences reinforce this idea.

1. Copy the following headings into your notebook. Be careful to leave enough space under each heading to record your answers. Complete the chart by answering the questions under each heading.

Situation	What object is exerting the force?	Upon which object does this force act?	Does the smaller object accelerate?	Was there contact between the objects?
A student pushes a small table across a floor.				
A baseball player hits a baseball with a baseball bat.				

Common sense tells you that there should be **contact** for one object to transmit a force to another object. You can never cause a table to move without contact. You can never hit a home run unless the bat hits the ball. This concept was so logical that the ancient Greeks developed a theory called the Effluvium theory that reinforced the idea that there must be contact before one object can interact with another. This theory was sufficient to satisfy the questions asked at that time, but during the Renaissance a new situation came to light. To help you understand the background of this situation, do the following questions.

2. Copy the following headings into your notebook. Be careful to leave enough space under each heading to record your answers. Complete the chart by answering the questions under each heading.

Situation	What object is exerting the force?	Upon which object does this force act?	Does the smaller object accelerate?	Was there contact between the objects?
An apple in a tree suddenly falls to the earth.				
A small piece of paper suddenly jumps to a charged rod held above the paper.				

3. When you look at your answer to question 2, it is easy to see that there is a distinct difference between questions 1 and 2. Describe the difference.

Check your answers by turning to the Appendix, Section 3: Activity 1.

The phenomenon of one object exerting a force on another object with no observable contact was just as startling to the Renaissance scientists as the television jumping up would be to you. What must be transmitting the force? The answer can be found in the work of an English physicist. Read the first paragraph on the top of page 426 of your textbook and answer the following questions.

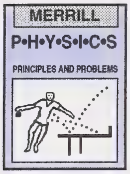
MERRILL P•H•Y•S•I•C•S PRINCIPLES AND PROBLEMS

4. What concept was suggested to explain the transmission of a force through space with no observable contact between objects?

5. Who suggested this concept?

Check your answers by turning to the Appendix, Section 3: Activity 1.

The introduction of the field theory to explain how a gravitational force $\left(\vec{F}_g\right)$ or an electrostatic force $\left(\vec{F}_e\right)$ can affect objects at a distance was an important development. Prior to this, people referred to the ability of one object to influence another without contact as the problem of action at a distance. It was a problem because it did not conform to common sense ideas about the universe. The field concept helped to solve this dilemma and, as you'll see in the next activity, helped to further unify the concepts of electrostatic and gravitational force.



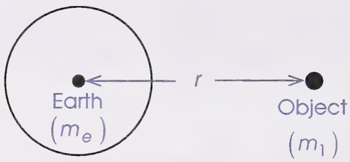
Activity 2: Developing the Electric Field Concept

The idea of a field was first introduced by Faraday to explain magnetic interactions that he had observed in his lab. This idea was so useful that it was later applied to both gravitational and electrostatic effects.

gravitational field – the space surrounding a mass in which other masses will experience a gravitational force

You have already studied the idea of a **gravitational field** in Physics 20. To quickly review the main ideas, read from the top of page 168 to the bottom of the first paragraph on page 169 in your textbook.

1. Consider an object $\left(m_1\right)$ that is a known distance (r) from the centre of the earth $\left(m_e\right)$.



   a. If the object falls to the earth, what must be acting on the object?

   b. Which object is producing this force?

   c. What is this force between two masses called?

   d. What equation can be used to calculate the force of gravity between any two masses?

   e. What is the direction of the force of gravity exerted by the earth on the object?

   f. Is the force of gravity exerted by the earth transmitted through space to the object with no observable contact?

   g. Will this force of gravity exerted by the earth influence the object no matter where the object is above the earth's surface?

gravitational field at a point – a vector that indicates the force per unit of mass

2. The **gravitational field at a point** can be represented by a vector, as shown in the following equation.

$$\vec{g} = \frac{\vec{F}_g}{m}$$

Gravitational field at a point → $\vec{g}$
$\vec{F}_g$ ← Gravitational force acting on a test mass
m ← Test mass

a. How does the direction of the gravitational field compare to the direction of the gravitational force acting on a test mass?

b. What are the units of gravitational field?

c. What is the value of the gravitational field near the surface of the earth? What other name is often used for this value?

3. The magnitude of the gravitational field vector can also be calculated with another equation. Copy the following flow chart into your notes and complete the flow chart to show the derivation of this equation.

$$F_g = \frac{Gm_e m}{r^2}$$

Substitute.

$$\boxed{F_g = mg} \rightarrow \boxed{g = \frac{F_g}{m}} \rightarrow \boxed{} \rightarrow \textbf{?}$$

Rearrange.

Cancel the test mass.

4. Refer to your answer to the previous question to answer this question.

a. What two variables influence the magnitude of the earth's gravitational field at a point in space?

b. What does the gravitational constant (G) indicate about the kind of objects that produce significant gravitational fields?

5. Use the values for the mass and average radius of the earth that are provided in the Physics 30 data sheets to calculate the magnitude of the earth's gravitational field near the surface of the planet.

Check your answers by turning to the Appendix, Section 3: Activity 2.

Both equations for calculating the magnitude of the gravitational field for a point in space contain a mass variable, but these masses refer to different things.

$$\boxed{g = \frac{F_g}{m}}$$

This is the mass that is brought into the gravitational field. This mass is known as the **test mass**.

$$\boxed{g = \frac{Gm_1}{r^2}}$$

This is the mass of the object that is producing the gravitational field. This mass is known as the **source mass**.

If you keep these ideas straight, these equations can be very helpful in problem solving.

6. Use the data in Table 8-1 on page 159 of your textbook to calculate the gravitational field strength on the surface of these planets.

   a. Mercury b. Mars c. Jupiter

7. Use your answers to the previous question to determine the weight of a 82.5-kg person on the surface of each planet listed in question 6.

Check your answers by turning to the Appendix, Section 3: Activity 2.

electric field – the space surrounding a charge in which other charges will experience an electrostatic force

electric field at a point – a vector that indicates the force per unit of a positive test charge

The same kind of ideas that you've been using with gravitational fields can also be applied to electric phenomena. After all, if a charged balloon can exert a force on the hairs of your head and make them stand on end, even though the balloon does not touch your hair, the balloon must be surrounding itself with an electric field.

The equation for the magnitude of the electric field at a point in space can be developed in a way that is very similar to the development of the gravitational field equation.

Magnitude of the electric field at a point.

$$\boxed{\left|\vec{E}\right| = \frac{F_e}{q}}$$

Magnitude of the electrostatic force acting on a test charge.

Test charge

The symbol for electric field, $\left|\vec{E}\right|$, could be confused with the symbol for energy, E. To avoid confusion, the electric field symbol will always be written with a vector arrow on top. When only the magnitude is required, absolute value signs will be used. Since energy is a scalar quantity, it would never be represented with vector notation.

8. Use the previous equation to determine the units for electric field.

9. A balloon exerts an electrostatic force of 3.5×10^{-4} N on a speck of dust that has a charge of 9.2×10^{-9} C. Calculate the magnitude of the electric field of the balloon at the point in space occupied by the dust speck.

10. If it was possible to place a 1.0-C charge in the position of the dust speck, what is the magnitude of the electrostatic force that the 1.0-C charge would experience?

Check your answers by turning to the Appendix, Section 3: Activity 2.

The magnitude of the electric field can be determined from another equation that is derived from Coulomb's law. Note the similarities to your earlier work with gravitational fields.

$$\left|\vec{E}\right| = \frac{F_e}{q}$$

$$F_e = \frac{kq_1q}{r^2}$$

Substitute.

$$\left|\vec{E}\right| = \frac{\left(\dfrac{kq_1q}{r^2}\right)}{q}$$

Cancel the test charge, q.

$$\left|\vec{E}\right| = \frac{kq_1}{r^2}$$

Magnitude of the electric field at a point

Charge of the object that is the source of the electric field

Distance between the source charge and the point in space

As was the case with the equations for the gravitational field, the two equations for the magnitude of the electric field require you to be very clear about the meanings of the variables.

$$\boxed{|\vec{E}| = \frac{F_e}{q}}$$

This is the charge of the object brought into the electric field. This charge is known as the **test charge**.

$$\boxed{|\vec{E}| = \frac{kq_1}{r^2}}$$

This is the charge of the object that is producing the electric field. This charge is known as the **source charge**.

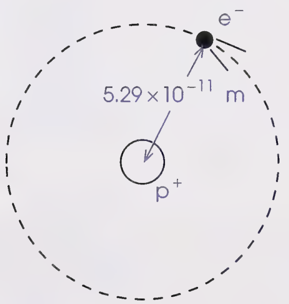
11. Refer to the derivation of the previous equation to answer these questions.

    a. What two variables influence the magnitude of the electric field of a source charge at a point in space?

    b. What does the Coulomb constant, *k*, indicate about the kind of objects that produce significant electric fields?

12. In another question you found the magnitude of the electric field of a balloon in the position occupied by a dust speck. This calculation could also be done in terms of the charge on the balloon. If the balloon had a charge of 4.8×10^{-7} C, and the point in space occupied by the dust speck was 33.7 cm away, calculate the magnitude of the electric field of the balloon.

13. In a simplified model of the hydrogen atom, a proton is the nucleus and an electron orbits 5.29×10^{-11} m away.



    a. Calculate the magnitude of the electric field at the location occupied by the electron.

b. Use your answer from question 13. a. to calculate the magnitude of the electrostatic force acting on the electron.

c. Check your answer to question 13. b. using Coulomb's law.

Check your answers by turning to the Appendix, Section 3: Activity 2.

You may have noticed that the initial definitions for electric field include vectors, and yet all the work to this point with electric fields has only involved magnitudes. It's reasonable to wonder why.

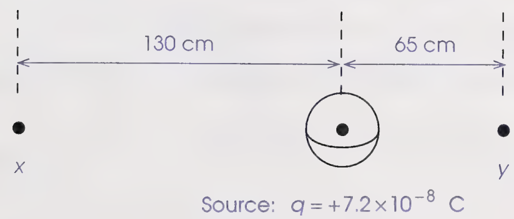
The reason is that the direction of an electric field vector is slightly more complicated than the direction of a gravitational field vector. Unlike gravitational effects, electrostatic effects can be both attractive and repulsive, depending on the signs of the charges. Gravitational force is always attractive and directed towards the centre of the source mass, but the electrostatic force can be directed either towards or away from the source charge, depending on the sign of the test charge. How can this be resolved?

The solution is for everyone to agree about the type of test charge that will be used. When you think about it, the test charge really doesn't affect the field – its only purpose is to test the presence of an electric field. Internationally, scientists have agreed that the electric field vector will always have a direction that is the same as the electrostatic force on a positive test charge. The vector versions of the electric field equations can now be written as follows:

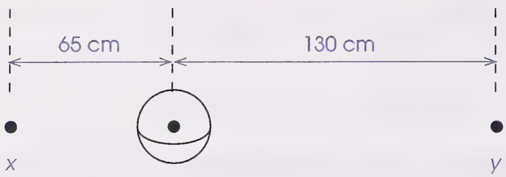
- $\vec{E} = \frac{F_e}{q}$ with direction determined by a positive test charge.
- $\vec{E} = \frac{kq_1}{r^2}$ with direction determined by a positive test charge.

14. Copy the following diagrams into your notebook. Be careful to leave enough space to record your answers. Complete the diagrams by calculating and then drawing the electric field vectors for points x and y. When you draw the field vectors, keep the lengths proportional.

a.



b.



Source: $q = -3.9 \times 10^{-6}$ C

15. What can be said about the direction of the electric field around a positive source? Explain.

16. Repeat question 15 for a negative source.

Check your answers by turning to the Appendix, Section 3: Activity 2.

Now that you've seen the recommended approach to electric field vectors in Physics 30, you can take a look at the textbook. The textbook does not use quite the same notation as was developed in this activity. You should use an approach that is consistent with what has been shown in this module.

MERRILL P•H•Y•S•I•C•S PRINCIPLES AND PROBLEMS

Read from the beginning of the second paragraph on page 426 to the end of the second paragraph on page 428 in your textbook. Be sure to carefully examine Figure 21-1 and Table 21-1 on page 428.

17. Do Practice Problem 1 on page 427 of your textbook.

18. Do Problem 4 in the right-hand column on page 444 of your textbook.

19. Use the information presented in the previous question and the Physics 30 data sheets to calculate the magnitude and sign of the net charge on the earth. You may be interested to know that the earth acquires this charge through global lightning storms. There are about 45 000 storms worldwide every day.

20. A tiny water droplet with a mass of only 2×10^{-11} kg remains suspended in the air due to the electric field of the earth being 150 N/C, downward.

    a. Is the water droplet positively or negatively charged? Explain.

    b. Calculate the charge on the water droplet.

c. Calculate the number of electrons that the water droplet has either gained or lost.

Check your answers by turning to the Appendix, Section 3: Activity 2.

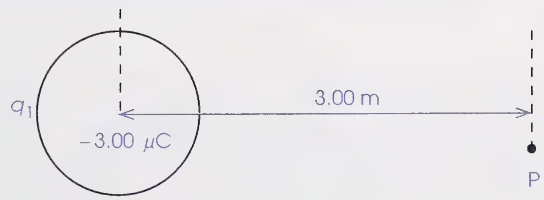
In the next questions you will discover what happens when charged particles interact with electric fields. This will also be a good opportunity to combine what you've just learned with other concepts from Physics 20 and Physics 30.

Before you analyse more complex situations, do the following problem to review how to set up a vector problem properly.

21. Calculate the magnitude and direction of an electric field at a point, P, 2.00 m to the right of a source charge of $+5.00 \times 10^{-6}$ C. Begin your solution with a labelled diagram.

The next problem will help illustrate the connections between electric fields and Coulomb's law.

22. a. Calculate the magnitude and direction of the electric field at point P.



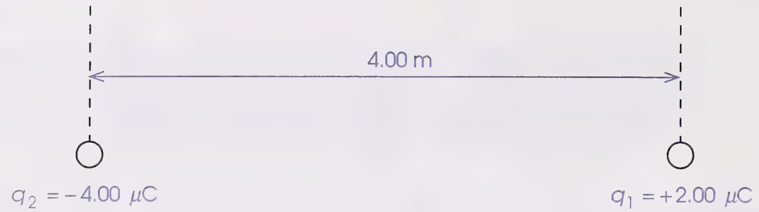
b. If another charge (q_2) of $-2.00\ \mu C$ is placed at point P, what will q_2 experience?

c. Using the electric field, calculate the force on q_2.

d. The force due to electrostatics on q_2 could also have been calculated using Coulomb's law. Show this calculation.

Electric fields also have connection to Newton's laws, as is illustrated in the following question.

23. Refer to the following diagram as you solve the parts of this question.



a. Calculate the magnitude of the electric field created by q_2 at the point in space occupied by q_1.

b. Calculate the magnitude and direction of the electrostatic force acting on q_1.

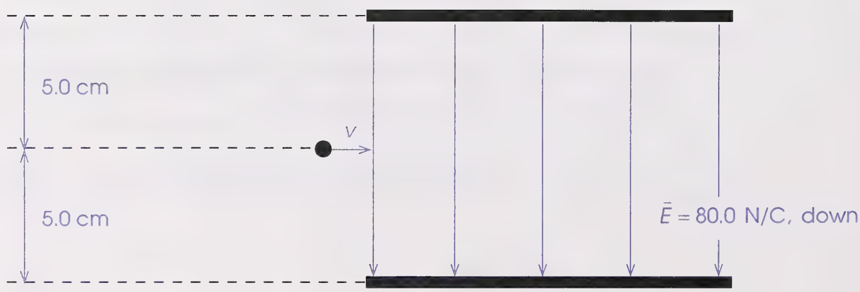
c. What is the magnitude and direction of the electrostatic force acting on q_2? Support your answer with one of Newton's laws.

d. Assume that q_1 has a mass of 3.4 mg and that no other forces are acting on it. Calculate the acceleration of q_1. Start your answer with one of Newton's laws.

Check your answers by turning to the Appendix, Section 3: Activity 2.

The concept of electric field can also be linked to the kinematics equations that you developed in Physics 20. The following question illustrates this connection.

24. The following diagram shows a particle with a charge of $-3.00\ \mu C$ moving through a region of uniform electric field. The particle has a velocity of 10.0 cm/s to the right as it moves through the electric field of 80.0 N/C, directed down. Note that the region of the electric field is between two plates that are 10 cm apart. The particle enters in the middle of this region.



a. Redraw the diagram in your notebook with the x- and y-axes drawn at the position of the charge. Include all relevant data.

b. Draw the force vectors acting on the charge on the diagram that you drew in question 24. a. Ignore gravity and consider air resistance to be negligible.

c. Identify the type of motion in the y-direction and the type of motion in the x-direction and list several equations which apply.

d. The mass of the particle is 30.0 mg. What is its horizontal speed 0.100 s after it has entered the electric field?

e. What is its vertical speed 0.100 s after entering the field?

f. Show the path that the charge will follow.

25. The previous question made the simplification that gravity could be ignored. A particle with a mass of 30.0 mg will actually be affected by the force of gravity.

a. Redraw the diagram for the previous question. Include an x-y axis, all the relevant data, and the forces acting on the object.

b. What kind of motion will the object have horizontally and vertically?

c. Find the net vertical force on the object.

d. Which plate will the object hit?

e. Find the horizontal displacement before the object hits the plate.

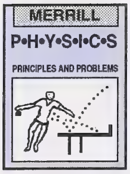
Check your answers by turning to the Appendix, Section 3: Activity 2.

In the next activity you will see how the concept of electric fields can be applied to the topic of lightning.

Activity 3: Picturing Electric Fields

Most applications of electric fields in the real world involve more than one source for the electric field. This means that the electric fields overlap, forming a resultant electric field.

In this activity you will learn to sketch the resultant electric field from more than one source. In the latter part of the activity you will employ many of the techniques that you used in Section 2 while working with Coulomb's law.



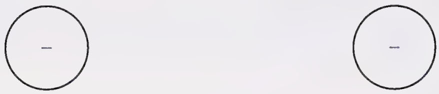
Read the section called Picturing the Electric Field on pages 428 and 429 of your textbook. When you have finished reading, do the following questions.

1. What is an electric field line?

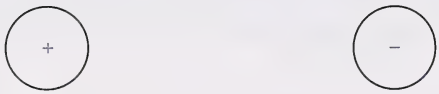
2. Explain how electric field lines are helpful even though they are imaginary.

3. What specifically can an electric field line show?

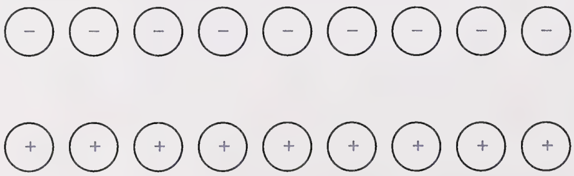
4. Copy the following diagrams into your notebook. Complete the diagrams by drawing the electric field lines between the sources. You will need to leave more space between the diagrams than what is indicated here.

a. 

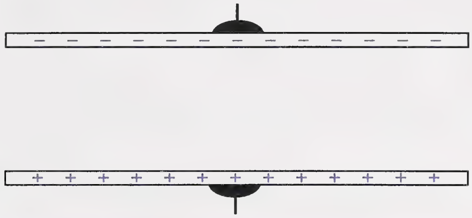
b. 

c. 

5. The following diagram shows a row of negative charges above a row of positive charges. Copy the diagram into your notebook. Complete the diagram by sketching the electric field in the region between the rows. Explain why you drew the lines the way you did.



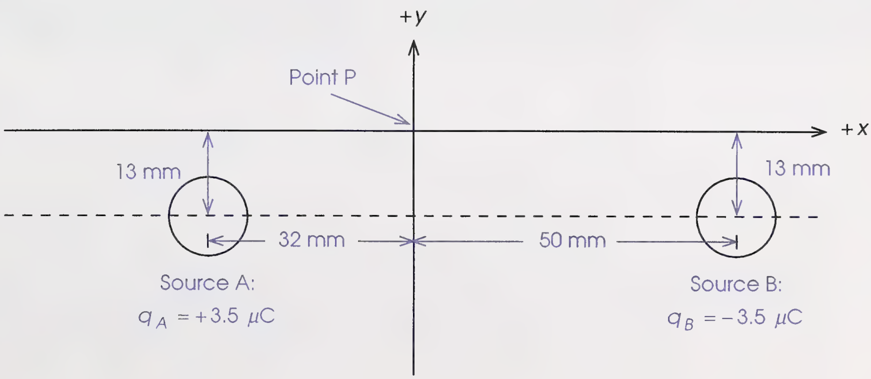
6. The following diagram shows two parallel metal plates. The diagram is an edge-on view. The top plate is negatively charged and the bottom plate is positively charged. Copy the diagram into your notebook. Complete the diagram by drawing the shape of the electric field lines in the region between the plates. Explain why you drew the lines the way you did.



Check your answers by turning to the Appendix, Section 3: Activity 3.

The previous questions were designed to be solved intuitively. In each case you predicted what a positive test charge would do in different places in the region between the charges. An alternative method is to do this mathematically. You would actually calculate the electric field vectors from each of the sources and then find the resultant electric field. The technique would be very similar to the method that you used in the previous section when you calculated the resultant electrostatic force of two charges acting on a third charge. The following questions will let you practise this method.

7. The following diagram shows two sources of electric fields, A and B. Both sources are 13 mm below point P. Source A is 32 mm to the left, while source B is 50 mm to the right.



a. Carefully copy this diagram into your notebook. Add the direction of each electric field.

b. Calculate the distance between each source and point P.

c. Determine the angle of each source from point P. Measure counterclockwise from the positive x-axis.

d. Calculate the magnitude of the electric field due to each source at point P.

e. Determine the direction of the electric field due to each source at point P.

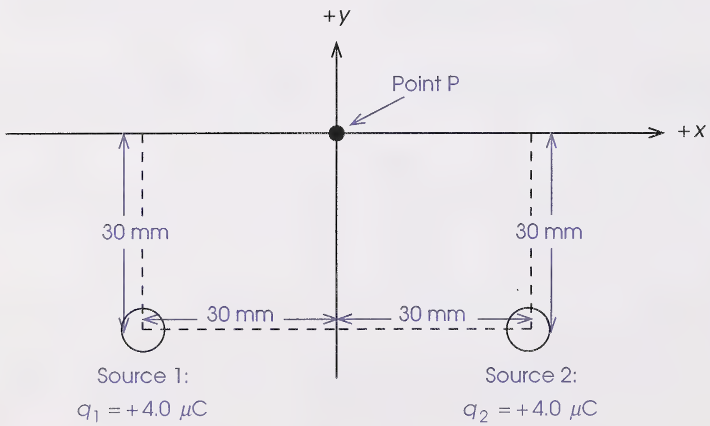
f. Calculate the magnitude and direction of the resultant electric field at point P.

g. Does your answer to question 7.f. match the direction of your answer to question 4.c.?

Check your answers by turning to the Appendix, Section 3: Activity 3.

You can often save yourself tremendous amounts of work by looking for symmetry in the question. You don't always have to go through all the steps that were shown in the previous question. The next three questions each have characteristics that make the solutions quite simple. Look for every opportunity to simplify the question before you start. The solutions will become simpler as you progress from one question to the next.

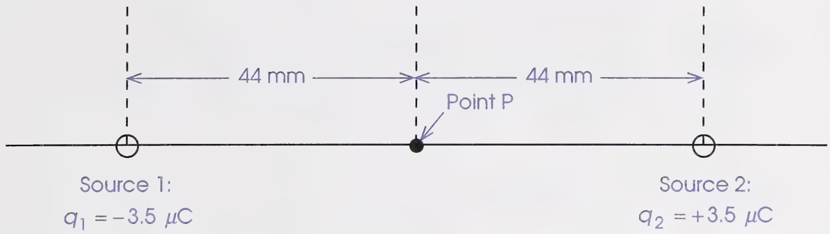
8.



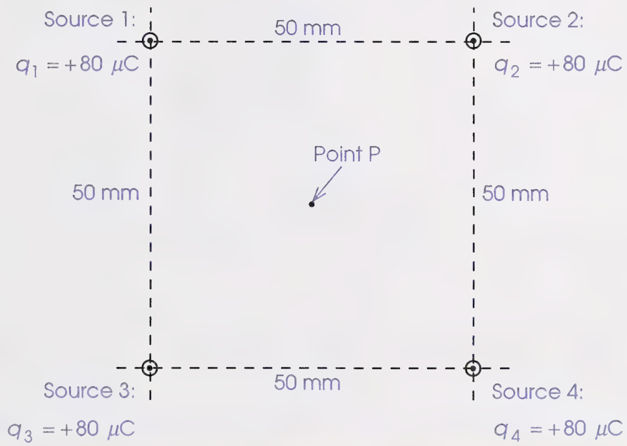
a. Calculate the magnitude and direction of the electric field at point P.

b. Does your answer to question 8.a. match your answer to question 4.b.?

9. Calculate the magnitude and direction of the electric field at point P.



10. Use the fact that point P is in the exact centre of the square to determine the magnitude and direction of the electric field at point P.



Check your answers by turning to the Appendix, Section 3: Activity 3.

Applying Electric Fields to Lightning

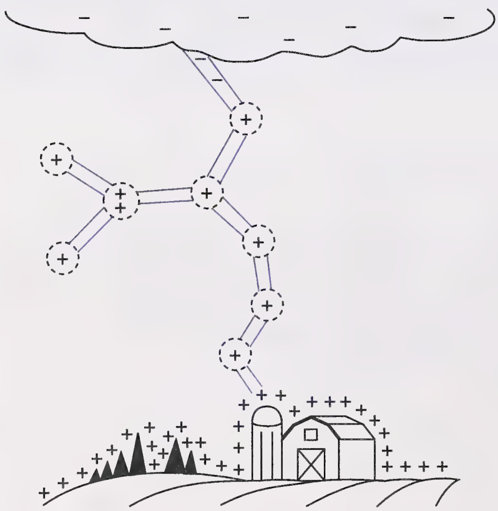
The concept of an electric field is very helpful in explaining some of the events related to electric storms. There is no single explanation that applies to every phenomenon related to thunderstorms. The state of the atmosphere is such that there are hundreds of variables that tend to make each discharge of lightning a unique event. The following explanations describe a typical chain of events.

The first step is the right atmospheric conditions that start the formation of the thundercloud. Usually this means moist, warm air being carried aloft by winds that rush to the centre of a low pressure area. As the warm air cools, the water condenses, releasing huge amounts of thermal energy. This causes more updrafts, which cause the water to rise further and freeze, releasing even more thermal energy. The rapid release of the thermal energy and the turbulent nature of the cloud can leave the cloud charged. The ground below it is then charged by induction.

11. Sketch this diagram in your notebook and complete it by drawing in the electric field lines between the cloud and the ground.

12. Where did the greatest concentration of field lines occur in the diagram that you drew?

Once the charge on the bottom of the cloud has built up beyond a certain critical value, the electrons that have accumulated on the bottom of the cloud begin to move to Earth.



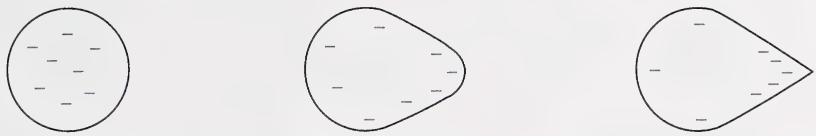
As the excess electrons begin to move to Earth, they are diverted by small pockets of positive ions in the atmosphere. A large pocket of positive ions may even pull part of the strike horizontally.

The heat created by the formation of a plasma in the air causes a compression wave to form and thunder is heard.

13. Why do lightning strikes look jagged?

14. Thunderclouds often have regions of water drops that are suspended inside the cloud by the strong electric fields within the cloud. How does this relate to the fact that large gushes of rain often accompany a large lightning strike?

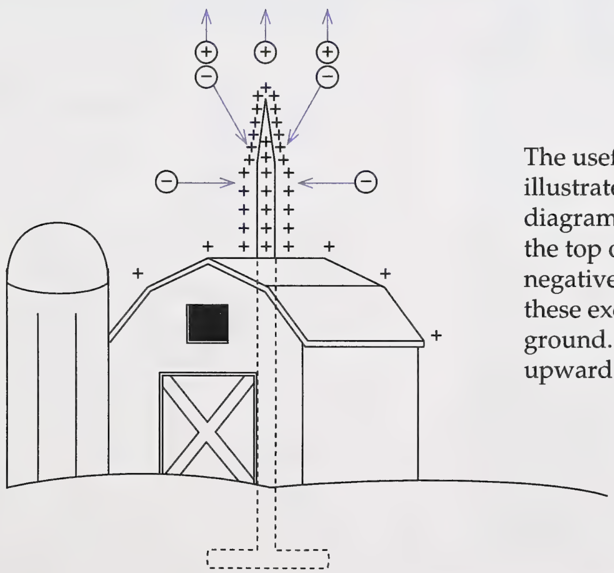
One of Benjamin Franklin's most useful inventions is the lightning rod. Franklin thought that the lightning rod would provide a safe way to discharge the region of the cloud above a building and avoid a major strike. The crucial part of the lightning rod's design is illustrated in the following diagrams.



Charge will be distributed evenly over the surface of a uniform sphere. As the sphere is made more pear-shaped, the charge begins to collect at the small end. If the sphere is drawn out to a sharp point, the charge will be concentrated mostly at the point.

15. Copy the previous diagrams into your notebook. Be careful to leave enough space to record your answers. Complete the diagrams by sketching electric field lines around each object.

16. If the air surrounding the three charged objects in the previous diagram had positive ions, where would you likely find the greatest concentration of these ions?



The usefulness of the lightning rod is illustrated in the accompanying diagram. The strong electric field at the top of the lightning rod attracts negative ions in the air and transfers these excess electrons safely to the ground. Positive ions are repelled upward towards the cloud.

17. Why is a lightning strike less likely to occur due to the presence of a lightning rod?

Check your answers by turning to the Appendix, Section 3: Activity 3.

Follow-up Activities

If you had difficulties understanding the concepts in the activities, it is recommended that you do the Extra Help. If you have a clear understanding of the concepts, it is recommended that you do the Enrichment.

Extra Help

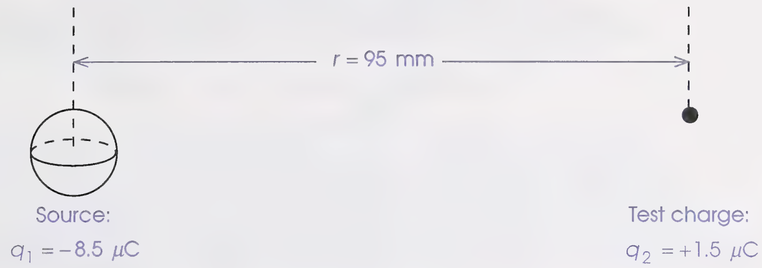
1. In Section 3 you studied the evolution of the concept of an electric field. To help you review this concept, copy the following headings into your notebook. Be careful to leave enough space under each heading to record your answers. Complete the chart by answering the question in the headings.

Question	Gravitational Field	Electric Field
What is the definition of the field?		
What is the symbol given to the field?		
What are the units of the field?		
What two equations are used to calculate the magnitude of the field?		
How is the direction of the field defined?		
Sketch the direction of the field around the object.	mass m_1	− charge q_1

2. What is a test mass or a test charge?

3. Why is it important that the or test charge be very small?

Use the following diagram to answer questions 4 through 6.



4. Calculate the magnitude of the electric field due to the source at the location occupied by the test charge.

5. Use Coulomb's law to check your previous calculation.

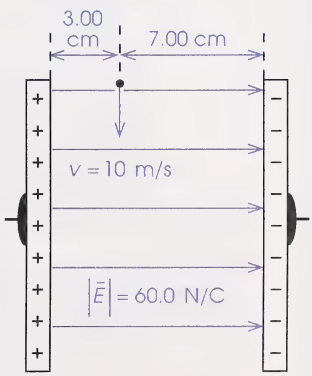
6. What would be the direction of the electric field at the location occupied by the test charge?

Check your answers by turning to the Appendix, Section 3: Extra Help.

Enrichment

Do **one** of the following Enrichment activities.

1. Consider the electric field between two **vertical** parallel plates. Find the vertical distance travelled by the charged object before it hits one of the plates. Note that the mass of the object is 5.00 mg and its charge is $+7.50\ \mu C$.



2. In laboratory tests, sharks are able to locate prey even when the food is wrapped in air-tight/water-tight packaging. Research how electric fields are used by sharks to locate their prey.

Check your answers by turning to the Appendix, Section 3: Enrichment.

Conclusion

In this section you first studied the need for a field theory. Then you determined how to calculate the magnitude and direction of an electric field around a given charged particle. Using these equations you were able to calculate the effect of an electric field on a charged particle in various situations.

Assignment Booklet

ASSIGNMENT

Turn to your Assignment Booklet and do the assignment for Section 3.

MODULE SUMMARY

In this module you first studied how the concept of electrostatic charges evolved from the early experiments of Franklin to the modern theory of static charges. Then you studied how Coulomb determined how to calculate the forces due to electrostatic charges by duplicating the work done by Cavendish on gravitational forces. Finally, you studied how electrostatic charges and forces created the field theory necessary to successfully understand the global concept of electrostatic charges.

This module primarily concentrated on the concepts surrounding stationary electrostatic charges, or static electricity. In the next module you will study the effects created when these charges begin to move, creating a branch of electricity called current electricity.

Appendix

Glossary

Suggested Answers

Glossary

amber: yellowish fossilized tree sap that is often used in jewellery

charging: the process of an object gaining electrons (negative charging) or losing electrons (positive charging)

charging by conduction: the process of charging an object by bringing it into contact with a charged body

charging by induction: the process of charging an object by bringing it close to a charged body while the object is being grounded

coulomb (C): the unit of charge in the SI system

Coulomb's law: the law which describes the electrostatic force between two charged objects

discharging: the process of losing charge and being neutralized

electric field: the space surrounding a charge in which other charges will experience an electrostatic force

electric field at a point: a vector that indicates the force per unit of a positive test charge

electric field line: an imaginary line that shows the electric field around a charged object

electric conductor: a material through which charge easily moves

electric insulator: a material through which charge does not easily move

field: a region of influence surrounding an object that can exert a force on another object

gravitational field: the space surrounding a mass in which other masses will experience a gravitational force

gravitational field at a point: a vector that indicates the force per unit of mass

grounding: the process of neutralizing the excess charge on an object by touching that object to the earth

ion: an atom that has gained or lost electrons, leaving it with a net negative or positive charge

law of conservation of charge: The total amount of charge in a closed system remains constant.

negatively charged: an object that has an excess of electrons

point charge: an idealized charge that is so small that it takes up no space

positively charged: an object that has a deficit of electrons

Suggested Answers

Section 1: Activity 1

1. The two tapes attracted each other as they approached each other.

This is a sample of Table 1. You should have observed the same effects as are shown in the chart.

Table 1

The Effects of Different Objects on the Overlapping Tapes		
Object	**Effect on Tape 1**	**Effect on Tape 2**
Comb	repel	attract
Rubber Rod	repel	attract
Glass Rod	attract	repel

2. The two tapes repelled each other as they approached each other.

This is a sample of Table 2. You should have observed the same effects as are shown in this chart.

Table 2

The Effects of Different Objects on the Side-by-Side Tapes		
Object	**Effect on Tape 1**	**Effect on Tape 2**
Comb	repel	repel
Rubber Rod	repel	repel
Glass Rod	attract	attract

3. a. The objects must be brought into contact or rubbed together.
   b. This type of interaction is called an electric interaction.
   c. *Electric* comes from the Greek word *elektron*, meaning "amber".
   d. After an object is rubbed, it is said to be in a charged condition.

4. a. There can be only two types of charges.
   b. Since there can be only two types of interactions, there can only be two types of charges.
   c. Franklin called these two charges positive and negative.

5.

Summary of the Behaviour of Charged Objects	
Description of Objects	**Behaviour**
The two objects have the same charge.	The objects repel each other.
The two objects have opposite charges.	The objects attract each other.

6. No, this experiment cannot determine the type of charge on each object. Although the investigation can help determine whether the objects have similar charges or different charges, you can't tell anything about the character of each charge unless you compare each to an object with a known charge.

7.

Assigning Charges to Objects		
Object	**First Part of the Investigation with Overlapping Tapes**	**Second Part of the Investigation with Side-by-Side Tapes**
Tape 1	–	–
Tape 2	+	–
Comb	–	–
Rubber Rod	–	–
Glass Rod	+	+

8. Electric forces can only appear after an object is rubbed, and then the force slowly leaks away. Gravitational forces do not require rubbing and do not leak away. Electric forces can attract and repel, while gravitational forces can only attract.

Section 1: Activity 2

1.

Date	Scientist	Part of Atom Discovered and Its Charge	Location of the Part of the Atom
1890	Thomson	negative electron	outside the nucleus
1909–1911	Rutherford	positive nucleus	the centre of the atom

2. There are the same numbers of negative electrons around the nucleus as there are positive charges within the nucleus.

3. a. Rubbing an object removes negative electrons from one object, making one object negative and leaving the other positive. **Note:** You have **not** created charges, you have only rearranged them. The law of conservation of charge is maintained because the total charge between the two objects remains constant.

b. Electrons are transferred.

c.

Object	Indicate whether the object has lost or gained electrons.	Indicate the type of ion formed in the object.	Indicate the net charge on the object.
Rubber	gained electrons	negative ion	negative
Wool/Fur	lost electrons	positive ion	positive

d. The nuclei make up the matter or mass of a substance and are bound to the lattice structure of a solid object. No mass (except the electrons) transfers between solids.

4. Electric conductors have electrons that are free to move from one atom to the next, while insulators have their electrons tightly bound to each atom.

5. Air can become a conductor if there are enough charges present to rip electrons off molecules in the air, leaving the molecules ionized. These ionized gas molecules, called a plasma, are able to conduct electricity.

6. a. The electric attraction between the negative electron and the positive nucleus holds the electrons within the atom.

   b. No, the electrons in the outermost orbit are loosely bound to the atom. They are called valence electrons.

7. a. A conductor is a substance that allows a charge to move easily within it.

   b. These electrons are called free electrons and are not tightly bound to any nucleus of any atom, and are free to move about.

   c. Copper, aluminum, and graphite are all good conductors.

8. a. An insulator is a substance which does not allow charges to move freely within it.

   b. All charges within an atom in an insulator are either bound to a particular nucleus or they are involved in a bond between neighbouring atoms. No electrons are free to move about.

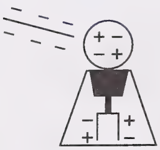
   c. Glass, dry wood, and cloth are all good insulators.

9. a. An electroscope is an instrument which is used to detect electric charge.

   b. i. knob
   ii. insulator
   iii. metal rod
   iv. metal leaves

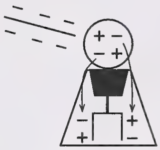
10. a. The following sequence of steps will charge the electroscope negatively by conduction: IV, VII, V, I.
    b. The following sequence of steps will charge the electroscope positively by conduction: III, II, VIII, VI.
    c. In charging by conduction, the charge on the electroscope is the same as the charge on the charging object.

11. Step 1



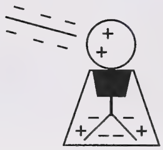
A negative rod is brought near the knob of the electroscope.

Step 2



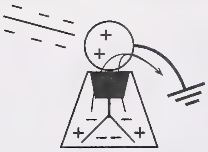
Electrons in the knob are repelled down to the leaves.

Step 3



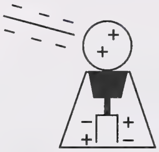
This causes the knob to become positive and the leaves negative.

Step 4



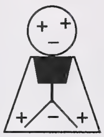
Grounding removes excess negative charge from the leaves.

Step 5



The ground is removed and the leaves come together.

Step 6



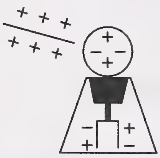
The negative rod is removed. Electrons redistribute and leaves diverge because of excess positive charge.

Note that in step 4 the ground provides the electrons with a path to escape the repulsive force of the negatively charged rod.

12. Grounding to Earth removes an excess of charge from an object by touching it to the ground.

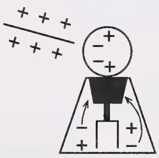
13. If you remove the rod first and then the ground, the electroscope will be neutral.

14. Step 1



A positive rod is brought near the electroscope.

Step 2

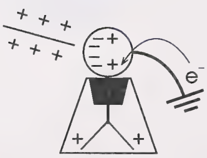


Free electrons from the leaves are attracted to the knob.

Step 3

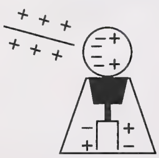
The leaves are left positive and they diverge.

Step 4



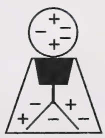
Grounding reduces excess positive charge in the leaves by bringing electrons into the leaves.

Step 5



The ground is removed and the leaves come together.

Step 6



The positive rod is removed, electrons redistribute, and leaves diverge because of excess negative charges.

15. When charging by induction, the final charge on the electroscope is opposite to the charge on the charging object.

16. When charging by conduction, the charging object has the same charge as the charged object. Charging by induction also involves a ground.

17. a. This charging occurred by friction or rubbing.
    b. The person acquired a negative charge and the cat's fur acquired a positive charge.
    c. Both the person and the cat are insulated.
    d. The negative charge on the person discharges.

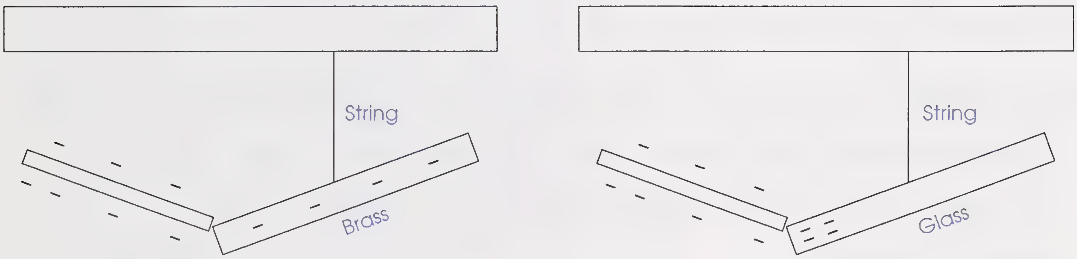
18. a. The earth acquires its charge by induction.
    b. The bottom of the cloud is negative and the top is positive.
    c. The earth's surface is positive.
    d. The air conductor is called a plasma.
    e. This discharge occurs between the negative bottoms and the positive tops of the clouds.

Section 1: Follow-up Activities

Extra Help

1. a. iii
   b. i
   c. ii

2. a.



   b. The brass is a conductor and the glass is an insulator. This means that electrons can readily move from one end of the brass rod to the other.

3. a. The top of the cloud has a positive charge.
   b. The bottom of the cloud has a negative charge.
   c. The roof of the barn has a positive charge.
   d. The ground below the barn has a negative charge.

4. a. The law of conservation of charge was used to determine the charge on the top of the cloud. Since the cloud is a neutral object, if there are excess electrons on the bottom of the cloud, these electrons must have been moved from the top of the cloud, leaving it positive.

   b. The bottom of the cloud became charged by the friction caused by the turbulent winds inside the cloud.

   c. The roof of the barn became positively charged by induction.

Enrichment

1. As clothes tumble in a dryer, the rubbing may cause electrostatic charges to build up, causing static cling. The molecules in an antistatic sheet provide a conductive path for charge discharge, thus removing static cling.

2. Eventually the sugar particles rub against each other and become charged by friction. The repulsion of two similarly charged sugar particles causes them to move apart and scatter farther from the centre.

3. Water molecules are polar, with one side positive due to hydrogen atoms and the other side negative due to the oxygen atom. When a negative rod is held near, attraction occurs to the positive end of the molecules (the end containing hydrogen). When a positive rod is held near, attraction occurs to the negative end of the molecules (the end containing the oxygen).

Section 2: Activity 1

1. The force of gravity is affected by the two masses involved and the distance between their centres.

2. As the masses increase, the force of gravity increases. This is a direct relationship.

3. Mathematically, the relationship is $F_g \propto m_1 m_2$.

4. As the distance between the two masses increases, the force of gravity decreases. This is an inverse square relationship.

5. Mathematically, the relationship is $F_g \propto \frac{1}{r^2}$.

6. The electrostatic force is affected by the two charges involved and the distance between their centres.

7. As the magnitudes of the two charges increase, the electrostatic force increases.

8. As the distance between the two charges increases, the electrostatic force decreases.

Section 2: Activity 2

1. There is an electrostatic force acting between balls A and B.

2. The force will be repulsive because the charges are both negative.

3. Ball A will rotate counterclockwise since it is repelled from ball B.

4. Since ball A is a conductor, as is ball B, charge will flow from one metal ball to the other until the charge on each is the same.

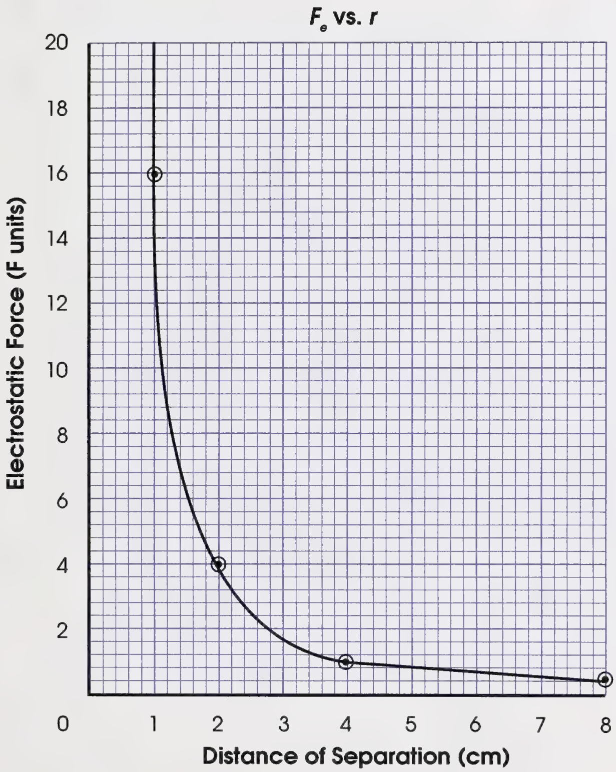
5. a. The total charge must be equivalent to q_B, as stated by the law of conservation of charge.

   b. Since they share charge on contact, the charge on ball A will be $\frac{1}{2}q_B$ and the charge on ball B will be $\frac{1}{2}q_B$.

6. Your chart should look similar to the chart shown.

Distance Between Two Charged Objects (r) in cm	Electrostatic Force (F) in F units
1.0	16.0
2.0	4.0
4.0	1.0
8.0	0.5

7.



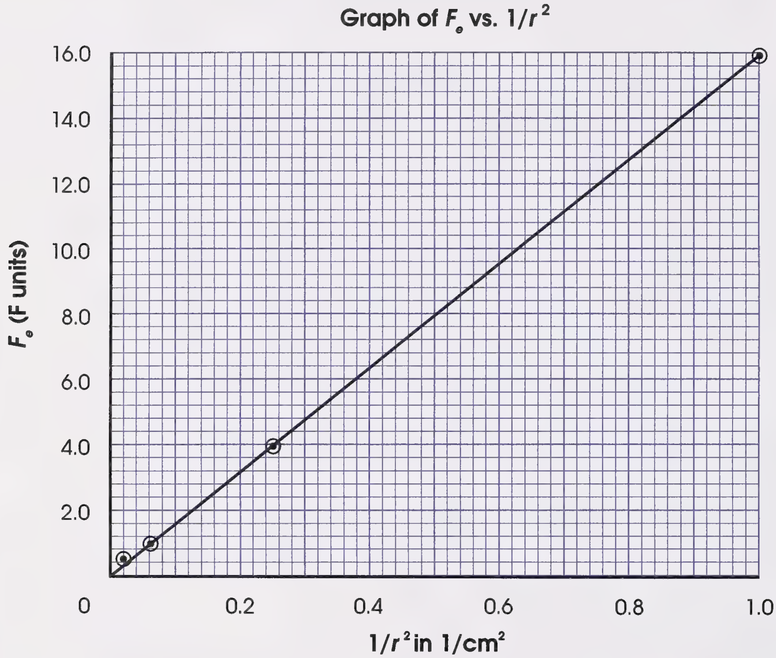
8. The graph is a smooth curve.

9. a. You could linearize the graph by squaring the r value and plotting F_e vs. $\frac{1}{r^2}$. This is because F_e is suspected to be similar to F_g.

b.

Distance (r) (cm)	$\frac{1}{r^2}$ $\left(\frac{1}{cm^2}\right)$	F_e (F units)
1.0	1.00	16.0
2.0	0.25	4.0
4.0	0.063	1.0
8.0	0.016	0.5

c.



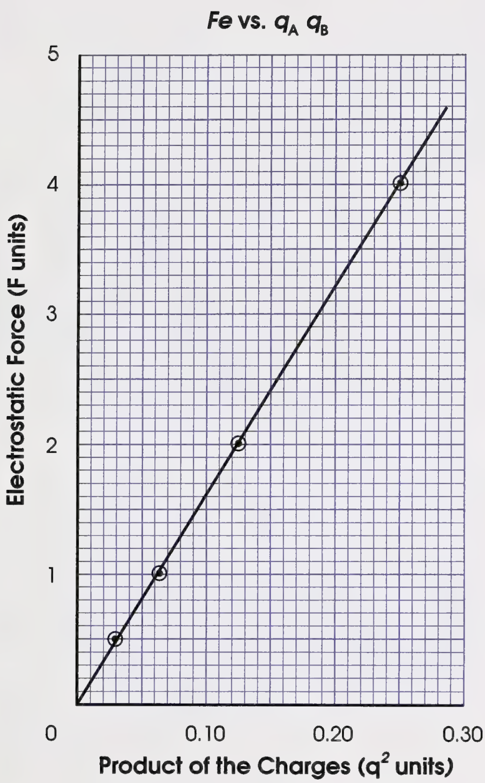
10. The mathematical expression is $F_e \propto \frac{1}{r^2}$. This is an **inverse squared** relationship.

11. Since $F_g \propto \frac{1}{r^2}$ and $F_e \propto \frac{1}{r^2}$, both relationships are the same.

12. Each metal ball will hold half the original charge. Therefore, each will hold $\frac{q}{2}$.

13. By touching ball B to ball C, the charge will split and ball B will have $\frac{1}{4}q$ and ball C will have $\frac{1}{4}q$. By neutralizing ball C each time and touching ball B, he can halve the charge on ball B each time.

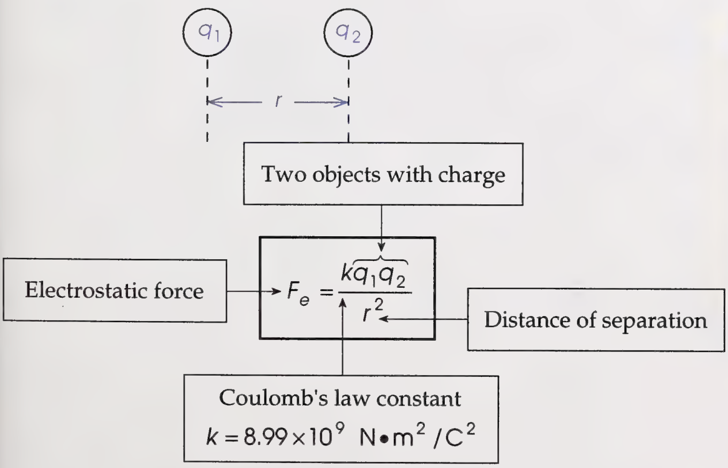
14.



15. The graph is a straight line.

16. This proves that $F_e \propto q_A q_B$.

17. Coulomb's Law



Quantity	Units
F_e	N
k	$\frac{N \bullet m^2}{C^2}$
q	C
r	m

18. a. $q_1 = 1.00\ \text{C}$

$q_2 = 1.00\ \text{C}$

$r = 1.00\ \text{m}$

$F_e = ?$

$$F_e = \frac{kq_1q_2}{r^2}$$

$$= \frac{\left(8.99\times10^9\ \text{N}\bullet\text{m}^2/\text{C}^2\right)(1.00\ \text{C})(1.00\ \text{C})}{(1.00\ \text{m})^2}$$

$$= 8.99\times10^9\ \text{N}$$

b. It would be exceptionally difficult to store this much charge on two objects so close together. If a cloud discharges about 1 C in a lightning bolt that can travel over 1 km through the air, it is difficult to imagine how you could put that much charge on each object without it grounding to the nearby equipment. The other difficulty concerns the force that would be required to hold the two objects in position while they repel each other. The force of 9×10^9 N is roughly equivalent to the weight of an object with a mass of 1 million t!

19. The electrostatic force on balloon 1 is 1×10^{-3} N, left.

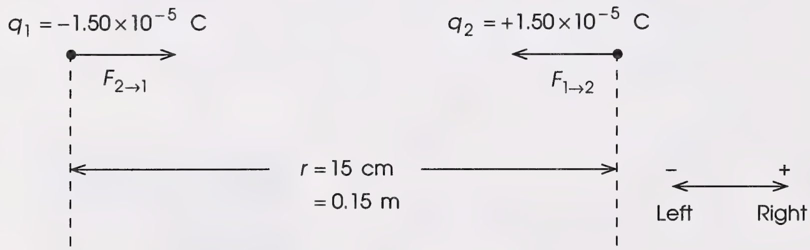
20. The electrostatic force on balloon 2 is 1×10^{-3} N, right.

21. The answers to the previous two questions illustrate Newton's third law, which states that if object 1 exerts a force on object 2, object 2 will exert an equal but opposite force on object 1.

Section 2: Activity 3

1. Textbook question 8:

Step 1: Draw a diagram showing all relevant data.



Step 2: Find the magnitude of the electrostatic force.

$$F_e = \frac{kq_1q_2}{r^2}$$

$$= \frac{\left(8.99\times10^9\ \text{N}\bullet\text{m}^2/\text{C}^2\right)\left(1.5\times10^{-5}\ \text{C}\right)\left(1.5\times10^{-5}\ \text{C}\right)}{(0.15\ \text{m})^2}$$

$$= 89.9\ \text{N}$$

$$= 90\ \text{N}$$

Step 3: Assess the directions of the forces and state the final answer.

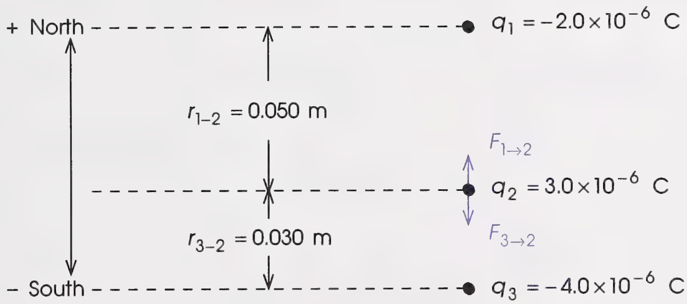
According to Newton's third law, the force acting on each of the charges is identical in size but opposite in direction.

$\vec{F}_{2\to1} = 90\ \text{N}$, towards charge 2

$\vec{F}_{1\to2} = 90\ \text{N}$, towards charge 1

2. Textbook question 15:

Step 1: Draw a diagram showing all the relevant data.



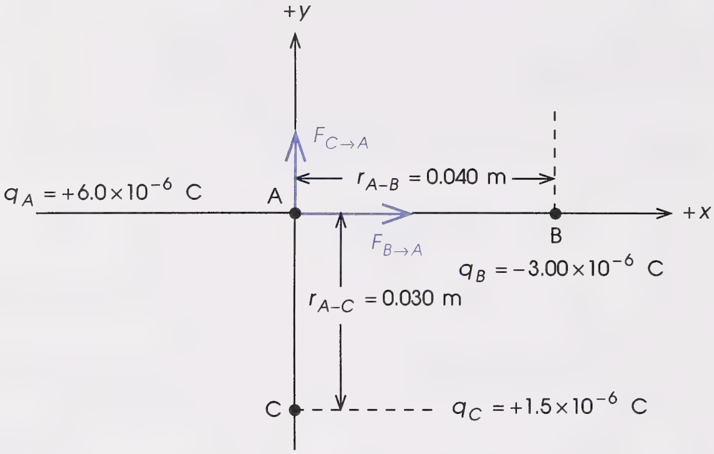
Step 2: Apply Newton's laws to find the magnitude of $\vec{F}_{net}$.

$$\begin{aligned}
\vec{F}_{net} &= \vec{F}_{1\to2} + \vec{F}_{3\to2} \\
\left|\vec{F}_{net}\right| &= \left|\vec{F}_{1\to2}\right| + \left(-\left|\vec{F}_{3\to2}\right|\right) \\
&= \left(\frac{kq_1q_2}{(r_{1-2})^2}\right) + \left(-\frac{kq_3q_2}{(r_{3-2})^2}\right) \\
&= \frac{(8.99\times10^9\ \text{N}\bullet\text{m}^2/\text{C}^2)(2.0\times10^{-6}\ \text{C})(3.0\times10^{-6}\ \text{C})}{(0.050\ \text{m})^2} + \\
&\quad \frac{-(8.99\times10^9\ \text{N}\bullet\text{m}^2/\text{C}^2)(4.0\times10^{-6}\ \text{C})(3.0\times10^{-6}\ \text{C})}{(0.030\ \text{m})^2} \\
&= 21.6\ \text{N} + (-119.9\ \text{N}) \\
&= -98.3\ \text{N} \\
&= -98\ \text{N}
\end{aligned}$$

Step 3: Assess the direction of the forces and state the final answer.

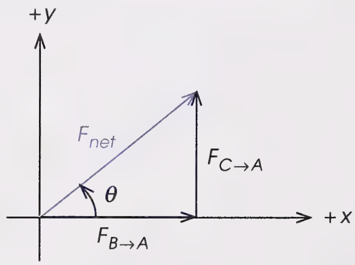
$$\begin{aligned}\vec{F}_{net} &= -98 \text{ N} \\ &= 98 \text{ N, south}\end{aligned}$$

3. Step 1: Redraw the diagram with point charges and show the relevant data and an *x-y* axis drawn through object A.



Step 2: Apply Newton's laws and draw a vector diagram to determine $\vec{F}_{net}$.

$$\vec{F}_{net} = \vec{F}_{B \to A} + \vec{F}_{C \to A}$$



Step 3: Find the magnitude of the net force.

$$C^2 = A^2 + B^2$$

$$\left|\vec{F}_{net}\right|^2 = \left|\vec{F}_{B \to A}\right|^2 + \left|\vec{F}_{C \to A}\right|^2$$

$$= \left(\frac{kq_Bq_A}{(r_{A-B})^2}\right)^2 + \left(\frac{kq_Cq_A}{(r_{A-C})^2}\right)^2$$

$$= \left(\frac{\left(8.99\times10^{9}\ \text{N}\bullet\text{m}^2/\text{C}^2\right)\left(3.00\times10^{-6}\ \text{C}\right)\left(6.0\times10^{-6}\ \text{C}\right)}{\left(0.040\ \text{m}\right)^2} \right)^2 +$$

$$\left(\frac{\left(8.99\times10^{9}\ \text{N}\bullet\text{m}^2/\text{C}^2\right)\left(1.5\times10^{-6}\ \text{C}\right)\left(6.0\times10^{-6}\ \text{C}\right)}{\left(0.030\ \text{m}\right)^2} \right)^2$$

$$= (101.1\ \text{N})^2 + (89.9\ \text{N})^2$$

$$= 10\,229\ \text{N}^2 + 8082\ \text{N}^2$$

$$= 18\,311\ \text{N}^2$$

$$\left|\vec{F}_{net}\right| = 135\ \text{N}$$

$$= 1.4\times10^{2}\ \text{N}$$

Step 4: Find the direction of the net force.

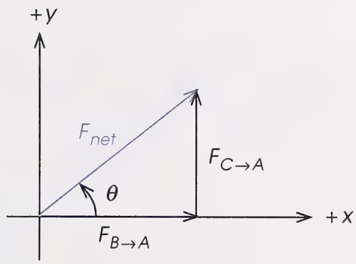
$$\tan\theta = \frac{F_{C\rightarrow A}}{F_{B\rightarrow A}}$$

$$= \frac{89.9\ \text{N}}{101.1\ \text{N}}$$

$$= 0.8892$$

$$\theta = 41.6°$$

$$= 42°$$

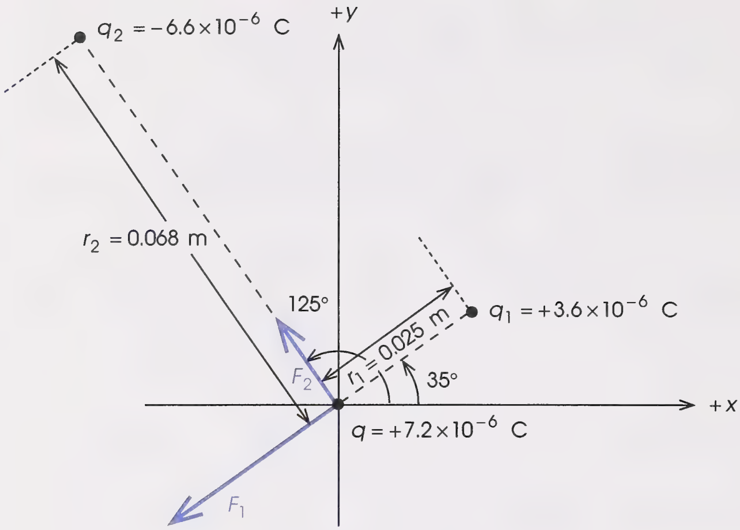


Step 5: State the final answer.

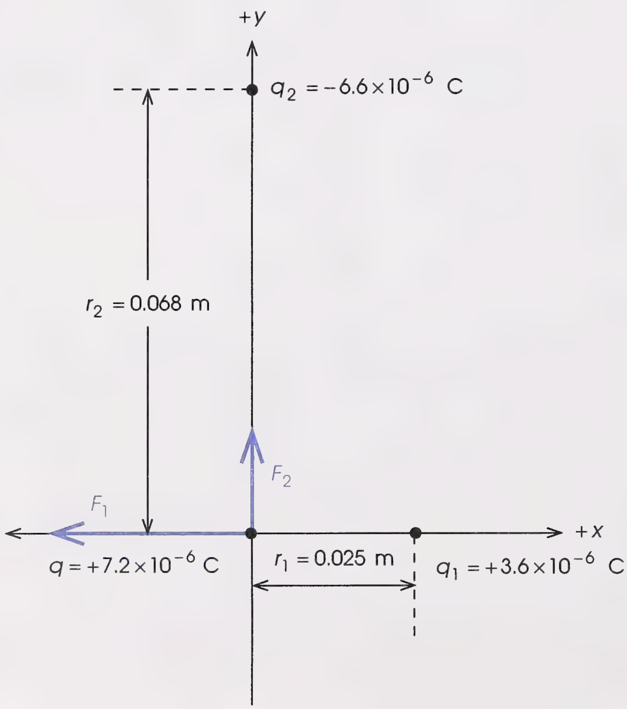
$$\vec{F}_{net} = 1.4\times10^{2}\ \text{N},\ 42°$$

4. Textbook question 18. c.:

Step 1: Draw the diagram with point charges and show all the relevant data and an x-y axis drawn through the charge, q. The diagram is shown on the next page.

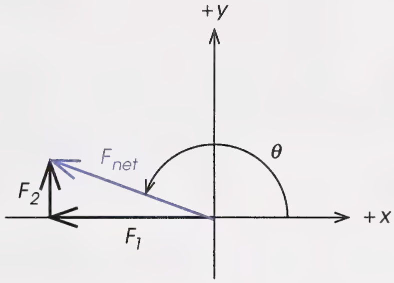


Step 2: Rotate both vectors clockwise 35° until they are aligned on the *x*- and *y*-axis. This will make the problem easier to solve. The only catch is that you will have to rotate the resultant 35° in the counter-clockwise direction when you are done.



Step 3: Apply Newton's laws and draw a vector diagram to determine $\vec{F}_{net}$.

$$\vec{F}_{net} = \vec{F}_1 + \vec{F}_2$$



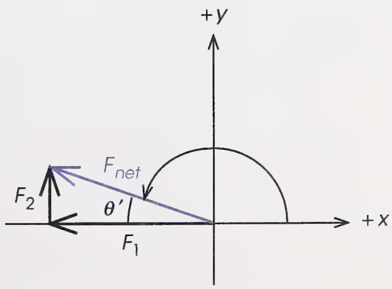
Step 4: Find the magnitude of the net force.

$$\begin{aligned}
C^2 &= A^2 + B^2 \\
\left|\vec{F}_{net}\right|^2 &= \left|\vec{F}_1\right|^2 + \left|\vec{F}_2\right|^2 \\
&= \left(\frac{kqq_1}{(r_1)^2}\right)^2 + \left(\frac{kqq_2}{(r_2)^2}\right)^2 \\
&= \left(\frac{(8.99 \times 10^9\ \text{N} \bullet \text{m}^2/\text{C}^2)(7.2 \times 10^{-6}\ \text{C})(3.6 \times 10^{-6}\ \text{C})}{(0.025\ \text{m})^2}\right)^2 + \\
&\quad \left(\frac{(8.99 \times 10^9\ \text{N} \bullet \text{m}^2/\text{C}^2)(7.2 \times 10^{-6}\ \text{C})(6.6 \times 10^{-6}\ \text{C})}{(0.068\ \text{m})^2}\right)^2 \\
&= (372.8\ \text{N})^2 + (92.4\ \text{N})^2 \\
&= 139\ 005\ \text{N}^2 + 8536\ \text{N}^2 \\
&= 147\ 540\ \text{N}^2 \\
\left|\vec{F}_{net}\right| &= 384\ \text{N} \\
&= 3.8 \times 10^2\ \text{N}
\end{aligned}$$

Step 5: Find the direction of the net force.

$$\begin{aligned}
\tan\theta' &= \frac{F_2}{F_1} \\
&= \frac{92.4\ \text{N}}{372.8\ \text{N}} \\
\theta' &= 13.9^\circ
\end{aligned}$$

$$\begin{aligned}
\theta &= 180^\circ - \theta' \\
&= 180^\circ - 13.9^\circ \\
&= 166.1^\circ \\
&= 166^\circ
\end{aligned}$$



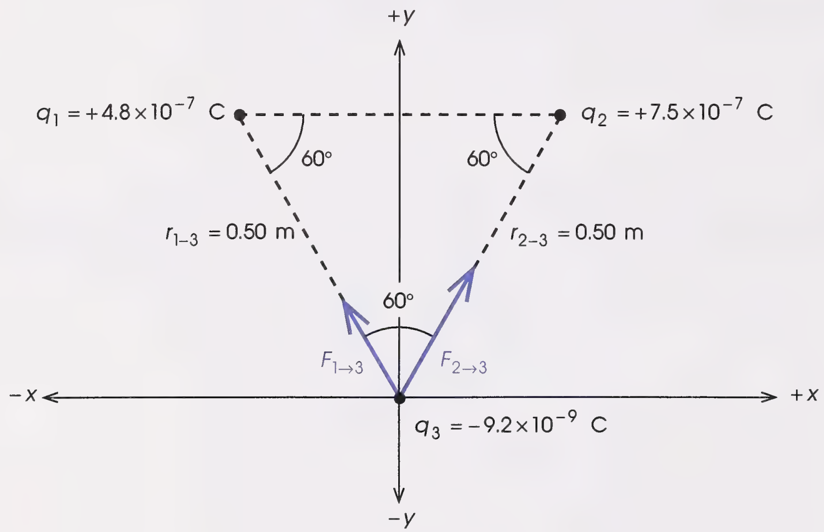
Step 6: Since both vectors were rotated 35° in the clockwise direction to simplify the solution, the resultant must now be rotated 35° in the counterclockwise direction.

$$\begin{aligned}\theta &= 166° + 35° \\ &= 201°\end{aligned}$$

Step 7: State the final answer.

$$\vec{F}_{net} = 3.8 \times 10^2 \text{ N, } 201°$$

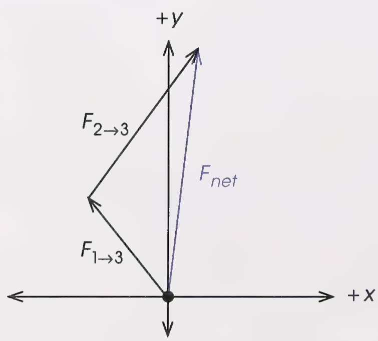
5. Step 1: Redraw the diagram with point charges and show all the relevant data and an *x*-*y* axis drawn through the dust speck.



Since the distances are all equal, the triangle is equilateral and the interior angles are each 60°.

Step 2: Find the net force.

$$\vec{F}_{net} = \vec{F}_{1\to3} + \vec{F}_{2\to3}$$



Step 3: Find the magnitude of the forces.

$$\left|\vec{F}_{1\to3}\right| = \frac{kq_1q_3}{(r_{1-3})^2}$$

$$= \frac{(8.99\times10^9\ \text{N}\bullet\text{m}^2/\text{C}^2)(4.8\times10^{-7}\ \text{C})(9.2\times10^{-9}\ \text{C})}{(0.50\ \text{m})^2}$$

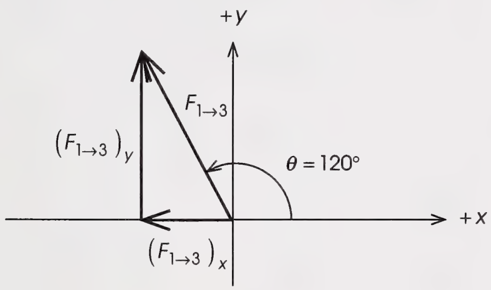
$$= 1.588\times10^{-4}\ \text{N}$$

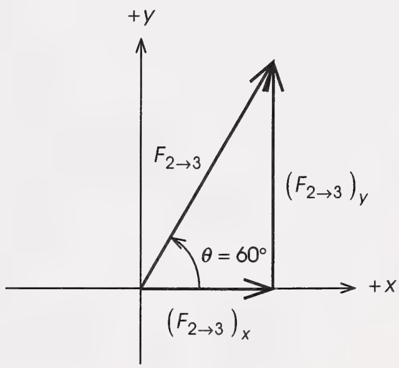
$$\left|\vec{F}_{2\to3}\right| = \frac{kq_2q_3}{(r_{2-3})^2}$$

$$= \frac{(8.99\times10^9\ \text{N}\bullet\text{m}^2/\text{C}^2)(7.5\times10^{-7}\ \text{C})(9.2\times10^{-9}\ \text{C})}{(0.50\ \text{m})^2}$$

$$= 2.481\times10^{-4}\ \text{N}$$

Step 4: Find the x- and y-components of the forces.





$$\left|\vec{F}_{1\to3}\right| = 1.588\times10^{-4}\ \text{N}$$

$$\left|\vec{F}_{1\to3}\right|_x = \left|\vec{F}_{1\to3}\right|\cos\theta$$

$$= (1.588\times10^{-4}\ \text{N})(\cos 120°)$$

$$= -7.94\times10^{-5}\ \text{N}$$

$$\left|\vec{F}_{1\to3}\right|_y = \left|\vec{F}_{1\to3}\right|\sin\theta$$

$$= (1.588\times10^{-4}\ \text{N})(\sin 120°)$$

$$= 1.38\times10^{-4}\ \text{N}$$

$$\left|\vec{F}_{2\to3}\right| = 2.481\times10^{-4}\ \text{N}$$

$$\left|\vec{F}_{2\to3}\right|_x = \left|\vec{F}_{2\to3}\right|\cos\theta$$

$$= (2.481\times10^{-4}\ \text{N})(\cos 60°)$$

$$= 1.24\times10^{-4}\ \text{N}$$

$$\left|\vec{F}_{2\to3}\right|_y = \left|\vec{F}_{2\to3}\right|\sin\theta$$

$$= (2.481\times10^{-4}\ \text{N})(\sin 60°)$$

$$= 2.15\times10^{-4}\ \text{N}$$

Step 5: Find the magnitude of the resultant.

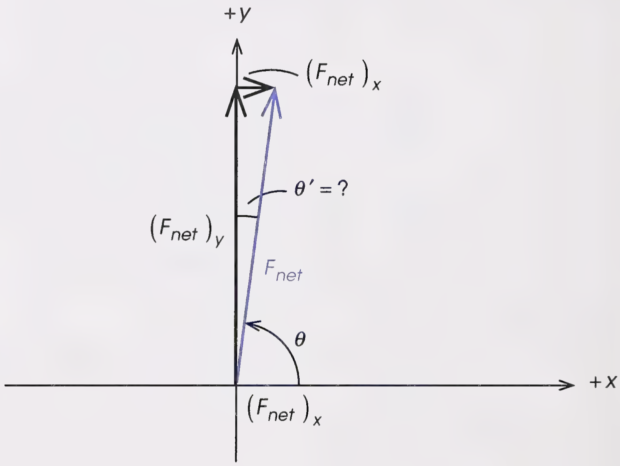
$$\left|\vec{F}_{net\,x}\right| = \left(-7.94\times10^{-5}\ \text{N}\right)+\left(1.24\times10^{-4}\ \text{N}\right)$$
$$= 4.46\times10^{-5}\ \text{N}$$

$$\left|\vec{F}_{net\,y}\right| = \left(1.38\times10^{-4}\ \text{N}\right)+\left(2.15\times10^{-4}\ \text{N}\right)$$
$$= 3.53\times10^{-4}\ \text{N}$$

$$\begin{aligned}
C^2 &= A^2 + B^2\\
\left|\vec{F}_{net}\right|^2 &= \left|\vec{F}_{net\,x}\right|^2 + \left|\vec{F}_{net\,y}\right|^2\\
&= \left(4.46\times10^{-5}\ \text{N}\right)^2 + \left(3.53\times10^{-4}\ \text{N}\right)^2\\
&= \left(1.989\times10^{-9}\ \text{N}^2\right)+\left(1.246\times10^{-7}\ \text{N}^2\right)\\
&= 1.266\times10^{-7}\ \text{N}^2\\
\left|\vec{F}_{net}\right| &= 3.56\times10^{-4}\ \text{N}
\end{aligned}$$

Step 6: Calculate the direction of the net force.

$$\begin{aligned}
\tan\theta' &= \frac{\left(F_{net}\right)_x}{\left(F_{net}\right)_y}\\
&= \frac{4.46\times10^{-5}\ \text{N}}{3.53\times10^{-4}\ \text{N}}\\
\theta' &= 7.2^\circ
\end{aligned}$$



$$\begin{aligned}
\theta &= 90^\circ - \theta'\\
&= 90^\circ - 7.2^\circ\\
&= 82.8^\circ\\
&= 83^\circ
\end{aligned}$$

Step 7: State the final answer.

$$\vec{F}_{net} = 3.56\times10^{-4}\ \text{N},\ 83^\circ$$

Section 2: Follow-up Activities

Extra Help

1.

Comparing $\vec{F}_e$ and $\vec{F}_g$	
Similiarities	**Differences**
• $\vec{F}_e$ and $\vec{F}_g$ can both attract. • $\vec{F}_e$ and $\vec{F}_g$ vary as $\frac{1}{r^2}$. • They are both vectors.	• $\vec{F}_e$ can also be repulsive. • The equations have different constants. • In most circumstances, $\vec{F}_e$ is a much larger force than $\vec{F}_g$.

2. $1\ \text{C} = 6.25\times10^{18}$ electrons

$4.50\ \text{C} = n$

$$\frac{1\ \text{C}}{4.50\ \text{C}} = \frac{6.25\times10^{18}\ \text{electrons}}{n}$$

$$n = \frac{(4.50\ \text{C})\left(6.25\times10^{18}\ \text{electrons}\right)}{1\ \text{C}}$$

$$= 2.81\times10^{19}\ \text{electrons}$$

3. $q_A = +5.00\times10^{-6}\ \text{C}$

$q_B = +1.00\times10^{-6}\ \text{C}$

$r = 0.100\ \text{m}$

$k = 8.99\times10^{9}\ \text{N}\bullet\text{m}^2/\text{C}^2$

$F_e = ?$

$$F_e = \frac{kq_1q_2}{r^2}$$

$$= \frac{\left(8.99\times10^{9}\ \text{N}\bullet\text{m}^2/\text{C}^2\right)\left(5.00\times10^{-6}\ \text{C}\right)\left(1.00\times10^{-6}\ \text{C}\right)}{(0.100\ \text{m})^2}$$

$$\vec{F}_e = 4.50\ \text{N, repelling}$$

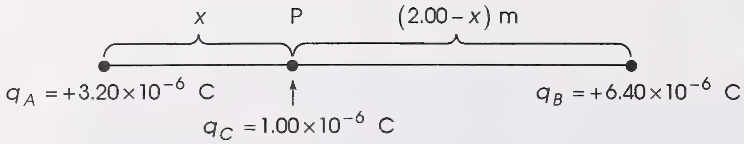
4. a. In this case the direction can be indicated by a sign convention, in which one direction is positive and the other is negative.

b. The origin of the *x*-*y* axis is placed directly on charge C. This is done because it is the forces acting on charge C that are the focus of the question.

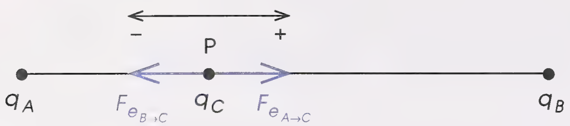
c. Since the three charges do not form a right angle, the equation $C^2 = A^2 + B^2$ cannot be immediately used with the forces $F_{B\rightarrow C}$ and $F_{A\rightarrow C}$. You must first find the *x*- and *y*-components of each of these forces.

Enrichment

1.



Let the position, P, be x m from q_A. At this position $\vec{F}_{net} = 0$.



$$\vec{F}_{net} = \vec{F}_{e_{B\to C}} + \vec{F}_{e_{A\to C}}$$

$$\left|\vec{F}_{net}\right| = -\left|\vec{F}_{e_{B\to C}}\right| + \left|\vec{F}_{e_{A\to C}}\right| = 0$$

$$\left|\vec{F}_{e_{B\to C}}\right| = \left|\vec{F}_{e_{A\to C}}\right|$$

$$\frac{kq_Bq_C}{r_{B-C}^{\;2}} = \frac{kq_Aq_C}{r_{A-C}^{\;2}}$$

Cancel like factors. $$\frac{\cancel{k}q_B\cancel{q_C}}{r_{B-C}^{\;2}} = \frac{\cancel{k}q_A\cancel{q_C}}{r_{A-C}^{\;2}}$$

Substitute. $$\frac{6.40 \times 10^{-6}\ \text{C}}{(2-x)^2} = \frac{3.20 \times 10^{-6}\ \text{C}}{x^2}$$

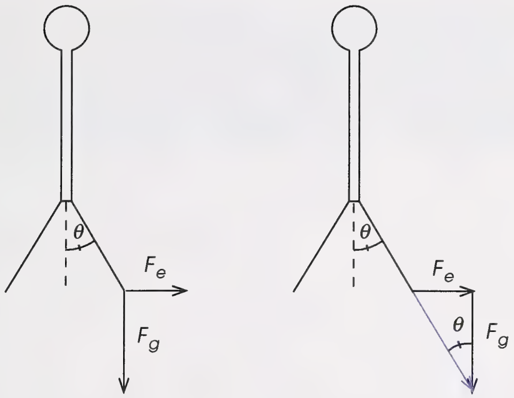
Simplify again. $$\frac{2}{(2-x)^2} = \frac{1}{x^2}$$

Take square roots and solve. $$\frac{1.414}{2-x} = \frac{1}{x}$$

$$x = 0.829\ \text{m}$$

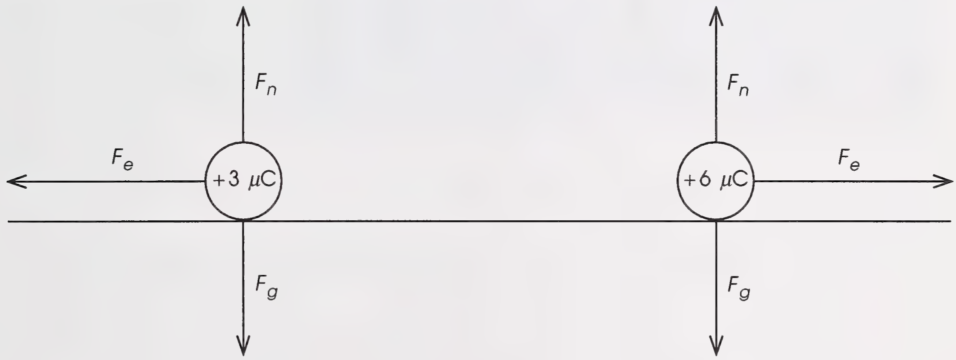
The net force on charge C is 0 N when C is 0.829 m from the 3.20×10^{-6}-C charge.

2. Textbook question 2.1:



Each leaf of the electroscope is acted on by two forces, the force of gravity and the electrostatic force. The resultant of these two forces determines the angle of the leaves.

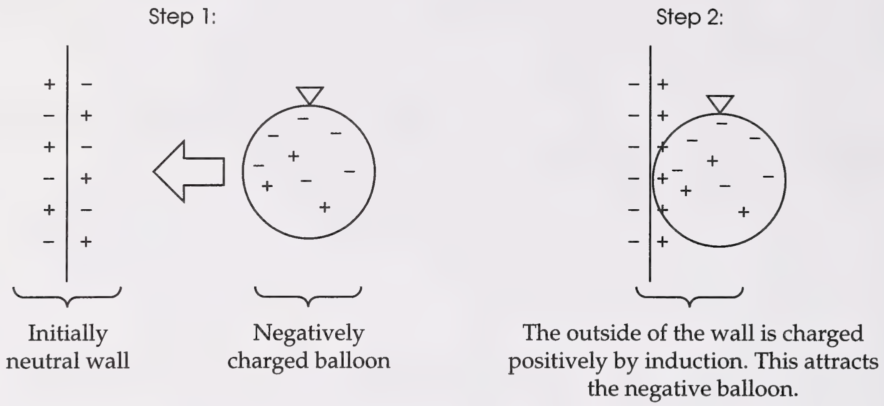
Textbook question 2.2:



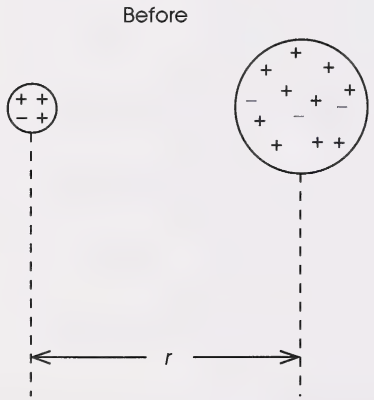
The arrows should show that the normal force and the gravitational force are the same length for each sphere. If the spheres had the same mass, the two arrows for the normal force and the two arrows for the gravitational force would also be the same length. The two arrows for the electrostatic force vectors should be the same length, in accordance with Newton's third law.

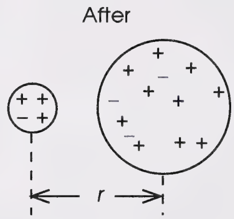
Textbook question 2.3:

Assuming that the balloon develops a negative charge from the wool, the following example summarizes the event.



Textbook question 2.4:





When the spheres are brought close together, the small amount of negative charge (electrons) left on the metal sphere is able to move in response to the presence of the small plastic sphere. The closeness of the negative charges reduces the repelling force on the small sphere because these charges will attract the small sphere.

Coulomb's law is only valid if the charge is distributed uniformly over the surface of each sphere so that the total charge distribution can be treated like a point charge at the centre.

Section 3: Activity 1

1.

Situation	What object is exerting the force?	Upon which object does this force act?	Does the smaller object accelerate?	Was there contact between the objects?
A student pushes a small table across a floor.	the student	the table	yes	yes
A baseball player hits a baseball with a baseball bat.	The baseball bat exerts a force on the ball.	the baseball	yes	yes

2.

Situation	What object is exerting the force?	Upon which object does this force act?	Does the smaller object accelerate?	Was there contact between the objects?
An apple in a tree suddenly falls to the earth.	the earth	the apple	yes	no
A small piece of paper suddenly jumps to a charged rod held above the paper.	the rod	the paper	yes	no

3. In question 2 there was no contact between objects, and yet the force was still able to act.

4. The concept of a field was introduced.

5. Faraday suggested this concept.

Section 3: Activity 2

1. a. A force must be acting on the object.
   b. The earth must be producing the force.

c. It is called a gravitational force.

d. The equation is $F_g = \frac{Gm_1m_2}{r^2}$.

e. The direction of the force of gravity is towards the centre of the earth.

f. There appears to be no visible contact.

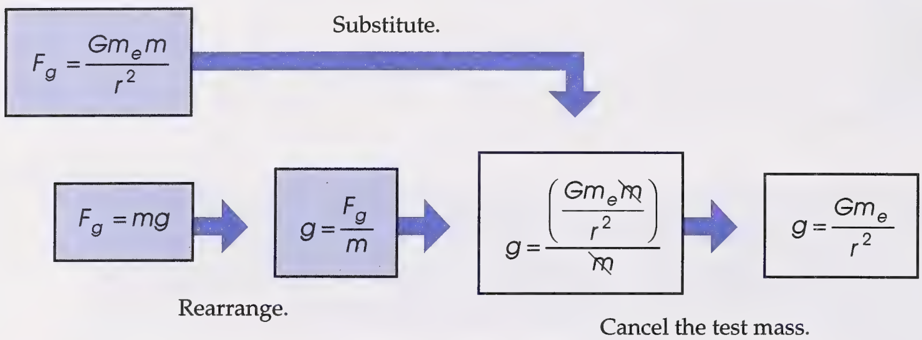
g. Yes, the force of gravity extends infinitely into space.

2. a. The gravitational field acts in the same direction as the gravitational force on an object.

   b. The units of gravitational field are force units divided by mass units, which is N/kg.

   c. The value for the gravitational field near the surface of the earth is 9.81 N/kg. The other name for this value is the acceleration due to gravity. In this case the units are simplified to $\mathrm{m/s^2}$.

3.



4. a. The earth's gravitational field is influenced by the mass of the earth and the distance from the centre of the earth for the distances beyond the earth's surface.

   b. The small value of G indicates that only large objects, like moons, planets, and stars, will have significant gravitational fields.

5. $G = 6.67 \times 10^{-11}\ \mathrm{N \bullet m^2/kg^2}$

   $m_e = 5.98 \times 10^{24}\ \mathrm{kg}$

   $r_e = 6.37 \times 10^{6}\ \mathrm{m}$

$$g = \frac{Gm_e}{(r_e)^2}$$

$$= \frac{\left(6.67 \times 10^{-11}\ \mathrm{N \bullet m^2/kg^2}\right)\left(5.98 \times 10^{24}\ \mathrm{kg}\right)}{\left(6.37 \times 10^{6}\ \mathrm{m}\right)^2}$$

$$= 9.83\ \mathrm{N/kg}$$

This calculation does not include the centripetal effects caused by the earth's spinning. This factor tends to reduce the average value of the downward acceleration.

6. a. Mercury

$m_M = 3.2 \times 10^{23}\ \text{kg}$

$r_M = 2.43 \times 10^{6}\ \text{m}$

$$g = \frac{Gm_M}{(r_M)^2}$$

$$= \frac{(6.67 \times 10^{-11}\ \text{N}\bullet\text{m}^2/\text{kg}^2)(3.2 \times 10^{23}\ \text{kg})}{(2.43 \times 10^{6}\ \text{m})^2}$$

$$= 3.6\ \text{N/kg}$$

b. Mars

$m_M = 6.42 \times 10^{23}\ \text{kg}$

$r_M = 3.38 \times 10^{6}\ \text{m}$

$$g = \frac{Gm_M}{(r_M)^2}$$

$$= \frac{(6.67 \times 10^{-11}\ \text{N}\bullet\text{m}^2/\text{kg}^2)(6.42 \times 10^{23}\ \text{kg})}{(3.38 \times 10^{6}\ \text{m})^2}$$

$$= 3.75\ \text{N/kg}$$

c. Jupiter

$m_J = 1.901 \times 10^{27}\ \text{kg}$

$r_J = 69.8 \times 10^{6}\ \text{m}$

$= 6.98 \times 10^{7}\ \text{m}$

$$g = \frac{Gm_J}{(r_J)^2}$$

$$= \frac{(6.67 \times 10^{-11}\ \text{N}\bullet\text{m}^2/\text{kg}^2)(1.901 \times 10^{27}\ \text{kg})}{(6.98 \times 10^{7}\ \text{m})^2}$$

$$= 26.0\ \text{N/kg}$$

7. a. Mercury

$m_p = 82.5\ \text{kg}$

$g = 3.6\ \text{N/kg}$

$F_g = ?$

$$F_g = mg$$

$$= (82.5\ \text{kg})(3.6\ \text{N/kg})$$

$$= 297\ \text{N}$$

$$= 3.0 \times 10^{2}\ \text{N}$$

b. Mars

$m_p = 82.5\ \text{kg}$

$g = 3.75\ \text{N/kg}$

$F_g = ?$

$$F_g = mg$$

$$= (82.5\ \text{kg})(3.75\ \text{N/kg})$$

$$= 309\ \text{N}$$

$$= 3.09 \times 10^{2}\ \text{N}$$

c. Jupiter

$m_p = 82.5 \text{ kg}$
$g = 26.0 \text{ N/kg}$
$F_g = ?$

$$\begin{aligned} F_g &= mg \\ &= (82.5 \text{ kg})(26.0 \text{ N/kg}) \\ &= 2145 \text{ N} \\ &= 2.15 \times 10^3 \text{ N} \end{aligned}$$

8. The units for electric field are force units divided by charge units, or N/C.

9. $F_e = 3.5 \times 10^{-4} \text{ N}$
$q = 9.2 \times 10^{-9} \text{ C}$
$|\vec{E}| = ?$

$$\begin{aligned} |\vec{E}| &= \frac{F_e}{q} \\ &= \frac{(3.5 \times 10^{-4} \text{ N})}{(9.2 \times 10^{-9} \text{ C})} \\ &= 3.8 \times 10^4 \text{ N/C} \end{aligned}$$

10. The value for electric field states that for this point in space, each coulomb will experience 3.8×10^4 N of force. This can also be solved mathematically.

$$\begin{aligned} |\vec{E}| &= \frac{F_e}{q} \\ F_e &= |\vec{E}|q \\ &= (3.8 \times 10^4 \text{ N/C})(1.0 \text{ C}) \\ &= 3.8 \times 10^4 \text{ N} \end{aligned}$$

11. a. The magnitude of the electric field is influenced by the charge on the source and the distance from the source.

b. The coulomb constant is such a large value that even sources with small amounts of charge can produce electric fields with large magnitudes.

12. $q_1 = 4.8 \times 10^{-7} \text{ C}$
$r = 33.7 \text{ cm} = 0.337 \text{ m}$
$|\vec{E}| = ?$

$$\begin{aligned} |\vec{E}| &= \frac{kq_1}{r^2} \\ &= \frac{(8.99 \times 10^9 \text{ N} \bullet \text{m}^2/\text{C}^2)(4.8 \times 10^{-7} \text{ C})}{(0.337 \text{ m})^2} \\ &= 3.8 \times 10^4 \text{ N/C} \end{aligned}$$

13. a. $r = 5.29 \times 10^{-11}$ m

$q_p = +1.60 \times 10^{-19}$ C

$|\vec{E}| = ?$

$$|\vec{E}| = \frac{kq_p}{r^2}$$

$$= \frac{(8.99 \times 10^9 \text{ N}\bullet\text{m}^2/\text{C}^2)(1.60 \times 10^{-19} \text{ C})}{(5.29 \times 10^{-11} \text{ m})^2}$$

$$= 5.14 \times 10^{11} \text{ N/C}$$

b. $|\vec{E}| = 5.14 \times 10^{11}$ N/C

$q_e = -1.60 \times 10^{-19}$ C

$F_e = ?$

$$|\vec{E}| = \frac{F_e}{q}$$

$$F_e = |\vec{E}|q$$

$$= (5.14 \times 10^{11} \text{ N/C})(1.60 \times 10^{-19} \text{ C})$$

$$= 8.22 \times 10^{-8} \text{ N}$$

The sign of the charge is not substituted into the equation. As was the case with Coulomb's law, the signs are used to determine the direction of the vectors.

c. $q_p = +1.60 \times 10^{-19}$ C

$q_e = -1.60 \times 10^{-19}$ C

$r = 5.29 \times 10^{-11}$ m

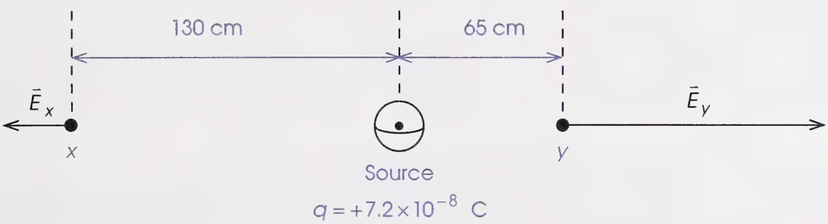
$F_e = ?$

$$F_e = \frac{kq_pq_e}{r^2}$$

$$= \frac{(8.99 \times 10^9 \text{ N}\bullet\text{m}^2/\text{C}^2)(1.60 \times 10^{-19} \text{ C})(1.60 \times 10^{-19} \text{ C})}{(5.29 \times 10^{-11} \text{ m})^2}$$

$$= 8.22 \times 10^{-8} \text{ N}$$

14. a.



$$|\vec{E}_x| = \frac{kq}{r^2}$$

$$= \frac{(8.99 \times 10^9 \text{ N}\bullet\text{m}^2/\text{C}^2)(7.2 \times 10^{-8} \text{ C})}{(1.30 \text{ m})^2}$$

$$= 383 \text{ N/C}$$

$\vec{E}_x = 3.8 \times 10^2$ N/C, away from the source

$\vec{E}_x = 3.8 \times 10^2$ N/C, left

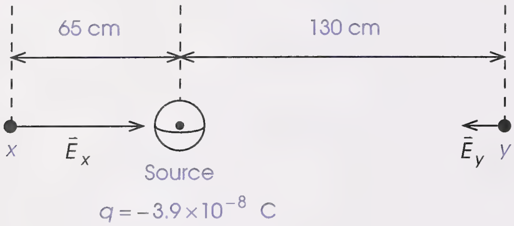
$$\left|\vec{E}_y\right| = \frac{kq}{r^2}$$
$$= \frac{\left(8.99\times10^9\ \text{N}\bullet\text{m}^2/\text{C}^2\right)\left(7.2\times10^{-8}\ \text{C}\right)}{\left(0.65\ \text{m}\right)^2}$$
$$= 1.53\times10^3\ \text{N/C}$$

$\vec{E}_y = 1.5\times10^3$ N/C, away from the source

$\vec{E}_y = 1.5\times10^3$ N/C, right

(In both cases a positive test charge would be repelled from the positive source.)

b.



$$\left|\vec{E}_x\right| = \frac{kq}{r^2}$$
$$= \frac{\left(8.99\times10^9\ \text{N}\bullet\text{m}^2/\text{C}^2\right)\left(3.9\times10^{-8}\ \text{C}\right)}{\left(0.65\ \text{m}\right)^2}$$
$$= 8.3\times10^2\ \text{N/C}$$

$\vec{E}_x = 8.3\times10^2$ N/C, towards the source

$\vec{E}_x = 8.3\times10^2$ N/C, right

$$\left|\vec{E}_y\right| = \frac{kq}{r^2}$$
$$= \frac{\left(8.99\times10^9\ \text{N}\bullet\text{m}^2/\text{C}^2\right)\left(3.9\times10^{-8}\ \text{C}\right)}{\left(1.30\ \text{m}\right)^2}$$
$$= 2.1\times10^2\ \text{N/C}$$

$\vec{E}_y = 2.1\times10^2$ N/C, towards the source

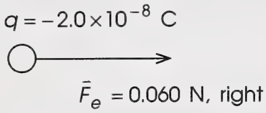
$\vec{E}_y = 2.1\times10^2$ N/C, left

(In both cases a **positive** test charge would be attracted to the negative source.)

15. The electric field vector will always point away from a positive source because a **positive test charge** will always be repelled from a positive source.

16. The electric field vector will always point towards a negative source because a **positive test charge** will always be attracted to a negative source.

17. Textbook question 1:



$$|\vec{E}| = \frac{F_e}{q}$$
$$= \frac{0.060\ \text{N}}{2.0\times10^{-8}\ \text{C}}$$
$$= 3.0\times10^{6}\ \text{N/C}$$

A positive test charge would go the opposite way of a negative test charge. The direction of the electric field must be left.

$\vec{E} = 3.0\times10^{6}$ N/C, left

18. Textbook question 4.a.:

A positively charged particle would be forced in the same direction as the electric field, which is downward.

Textbook question 4.b.

$\vec{E} = 150$ N/C, downward

$q_p = +1.60\times10^{-19}$ C

$F_e = ?$

$$|\vec{E}| = \frac{F_e}{q_p}$$
$$F_e = |\vec{E}|q_p$$
$$= (150\ \text{N/C})(1.60\times10^{-19}\ \text{C})$$
$$= 2.40\times10^{-17}\ \text{N}$$

$\vec{F}_e = 2.40\times10^{-17}$ N, downward

Textbook question 4.c.:

$m = 1.7\times10^{-27}$ kg

$g = 9.81\ \text{m/s}^2$

$F_g = ?$

$$F_g = mg$$
$$= (1.7\times10^{-27}\ \text{kg})(9.81\ \text{m/s}^2)$$
$$= 1.7\times10^{-26}\ \text{N}$$

The electrostatic force is much larger than the gravitational force.

19. $\vec{E} = 150$ N/C, downward

$r_e = 6.37\times10^{6}$ m

$q_e = ?$

$$|\vec{E}| = \frac{kq_e}{r^2}$$
$$q_e = \frac{|\vec{E}|r^2}{k}$$
$$= \frac{(150\ \text{N/C})(6.37\times10^{6}\ \text{m})^2}{(8.99\times10^{9}\ \text{N}\bullet\text{m}^2/\text{C}^2)}$$
$$= 6.77\times10^{5}\ \text{C}$$

Since the electric field points to the earth, the earth must be a negative source. Therefore, the charge on the earth is -6.77×10^{5} C.

20. a. If the water drop is suspended, the downward force of gravity must be balanced by the upward electrostatic force. Since the electric field is downward, a positive water drop would experience a downward electrostatic force. This is not right. It follows that a negative water drop would experience an upward electrostatic force. The water drop must be negative.

b. $m = 2.0 \times 10^{-11}$ kg

$g = 9.81\ \text{m/s}^2$

$q = ?$

$\vec{E} = 150$ N/C, downward

$$F_g = F_e$$

Since the drop is suspended, these forces balance each other.

$$mg = q\left|\vec{E}\right|$$

$$q = \frac{mg}{\left|\vec{E}\right|} = \frac{\left(2.0 \times 10^{-11}\ \text{kg}\right)\left(9.81\ \text{m/s}^2\right)}{150\ \text{N/C}} = 1.3 \times 10^{-12}\ \text{C}$$

c. $q = 1.3 \times 10^{-12}$ C

$1\text{e} = 1.60 \times 10^{-19}$ C

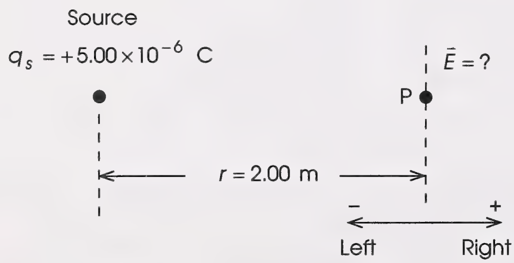
$n = ?$

$$\frac{1\ \text{electron}}{1.60 \times 10^{-19}\ \text{C}} = \frac{n}{1.3 \times 10^{-12}\ \text{C}}$$

$$n = \frac{(1\ \text{electron})\left(1.3 \times 10^{-12}\ \text{C}\right)}{\left(1.60 \times 10^{-19}\ \text{C}\right)} = 8.1 \times 10^{6}\ \text{electrons}$$

Since the water drop is negative, it must have gained 8.1×10^{6} electrons.

21. Step 1: Draw a diagram that shows the data given and the sign convention.



Step 2: Solve for the magnitude of the electric field.

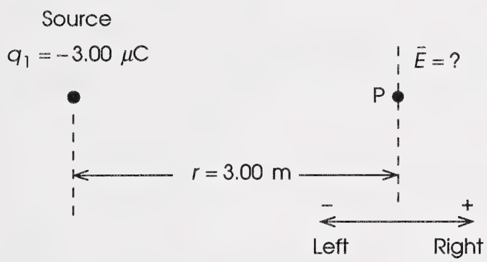
$$\left|\vec{E}\right| = \frac{kq_s}{r^2} = \frac{\left(8.99 \times 10^{9}\ \text{N}\bullet\text{m}^2/\text{C}^2\right)\left(5.00 \times 10^{-6}\ \text{C}\right)}{(2.00\ \text{m})^2} = 1.12 \times 10^{4}\ \text{N/C}$$

Step 3: Solve for the direction of the electric field. Since a positive test charge at P would be forced to the right, the direction of the electric field would also be to the right.

Step 4: State the magnitude and direction of the electric field.

$$\begin{aligned}\vec{E} &= +1.12\times 10^{4}\ \text{N/C}\\ &= 1.12\times 10^{4}\ \text{N/C, right}\end{aligned}$$

22. a. Step 1: Draw a diagram that shows the data given and the sign convention.



Step 2: Solve for the magnitude of the electric field.

$$\begin{aligned}|\vec{E}| &= \frac{kq_1}{r^2}\\ &= \frac{(8.99\times 10^{9}\ \text{N}\bullet\text{m}^2/\text{C}^2)(3.00\times 10^{-6}\ \text{C})}{(3.00\ \text{m})^2}\\ &= 2.997\times 10^{3}\ \text{N/C}\\ &= 3.00\times 10^{3}\ \text{N/C}\end{aligned}$$

Step 3: Solve for the direction of the electric field. Since a positive test charge at P would be forced to the left, the direction of the electric field would also be to the left.

Step 4: State the magnitude and direction of the electric field.

$$\begin{aligned}\vec{E} &= -3.00\times 10^{3}\ \text{N/C}\\ &= 3.00\times 10^{3}\ \text{N/C, left}\end{aligned}$$

b. The charge, q_2, will experience a repulsive force due to the electric field of q_1.

c. $|\vec{E}| = 2.997\times 10^{3}\ \text{N/C}$

$q_2 = -2.00\ \mu C$

$\vec{F}_e = ?$

Step 1: Calculate the magnitude of $\vec{F}_e$.

$$\vec{F}_e = \vec{E}q$$
$$\left|\vec{F}_e\right| = \left|\vec{E}\right| q$$
$$= \left(2.997\times10^{3}\ \text{N/C}\right)\left(2.00\times10^{-6}\ \text{C}\right)$$
$$= 5.994\times10^{-3}\ \text{N}$$
$$= 5.99\times10^{-3}\ \text{N}$$

Step 2: Since the two charges are both negative, the direction of the force on q_1 will be repulsive, or to the right.

Step 3: State the final answer.

$$\vec{F}_e = +5.99\times10^{-3}\ \text{N}$$
$$= 5.99\times10^{-3}\ \text{N, right}$$

d. $q_1 = -3.00\ \mu\text{C}$

$q_2 = -2.00\ \mu\text{C}$

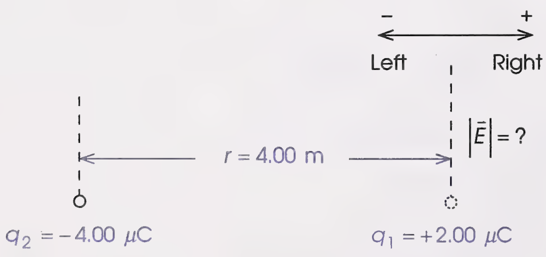
$k = 8.99\times10^{9}\ \text{N}\bullet\text{m}^2/\text{C}^2$

$r = 3.00\ \text{m}$

$\vec{F}_e = ?$

$$\left|\vec{F}_e\right| = \frac{kq_1q_2}{r^2}$$
$$= \frac{\left(8.99\times10^{9}\ \text{N}\bullet\text{m}^2/\text{C}^2\right)\left(3.00\times10^{-6}\ \text{C}\right)\left(2.00\times10^{-6}\ \text{C}\right)}{\left(3.00\ \text{m}\right)^2}$$
$$= 5.99\times10^{-3}\ \text{N}$$
$$\vec{F}_e = 5.99\times10^{-3}\ \text{N, right}$$

23. a.



$q_2 = -4.00\ \mu\text{C}$

$r = 4.00\ \text{m}$

$\left|\vec{E}\right| = ?$

$$\left|\vec{E}\right| = \frac{kq_2}{r^2}$$
$$= \frac{\left(8.99\times10^{9}\ \text{N}\bullet\text{m}^2/\text{C}^2\right)\left(4.00\times10^{-6}\ \text{C}\right)}{\left(4.00\ \text{m}\right)^2}$$
$$= 2.248\times10^{3}\ \text{N/C}$$
$$= 2.25\times10^{3}\ \text{N/C}$$

b. $\left|\vec{E}\right| = 2.248 \times 10^{3}\ \text{N/C}$
$q_1 = +2.00\ \mu\text{C}$
$\vec{F}_e = ?$

$$\left|\vec{E}\right| = \frac{F_e}{q}$$
$$\begin{aligned} F_e &= \left|\vec{E}\right| q \\ &= \left(2.248 \times 10^{3}\ \text{N/C}\right)\left(2.00 \times 10^{-6}\ \text{C}\right) \\ &= 4.496 \times 10^{-3}\ \text{N} \\ &= 4.50 \times 10^{-3}\ \text{N} \end{aligned}$$

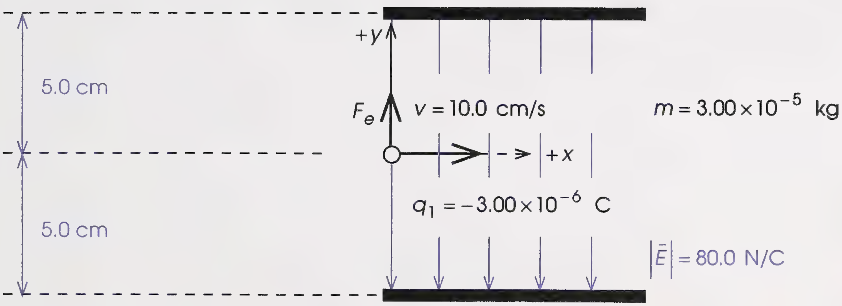
Since the positive charge would be attracted to the negative source, the electrostatic force is $4.50 \times 10^{-3}\ \text{N}$, left.

c. The electrostatic force acting on q_2 will be equal to the force on q_1 but will be in the opposite direction. Therefore, the force on q_2 will be $4.50 \times 10^{-3}\ \text{N}$, right. This is in accordance with Newton's third law.

d. $m = 3.4\ \text{mg} = 3.4 \times 10^{-6}\ \text{kg}$
$\vec{F} = 4.50 \times 10^{-3}\ \text{N, left}$
$\vec{a} = ?$

$$\vec{F} = m\vec{a}$$
$$\begin{aligned} \vec{a} &= \frac{\vec{F}}{m} \\ &= \frac{-4.50 \times 10^{-3}\ \text{N}}{3.4 \times 10^{-6}\ \text{kg}} \\ &= -1.32 \times 10^{3}\ \text{m/s}^2 \\ &= 1.32 \times 10^{3}\ \text{m/s}^2\text{, left} \end{aligned}$$

24. a.



b. This question is answered on the previous diagram.

c. The object will have only one force acting on it and since this force is unbalanced, the object will accelerate vertically in the direction of the force. The object will have uniform motion horizontally, since there are no forces acting in this direction.

Vertically:

$$F = ma$$

$$d = v_1 t + \frac{1}{2}at^2$$

$$|\vec{F}_e| = |\vec{E}|q$$

Horizontally:

$$d = vt$$

d. $m = 30.0 \text{ mg} = 3.00 \times 10^{-5} \text{ kg}$

$v_x = 10.0 \text{ m/s}$ because it is a constant speed

e. Vertically:

$v_i = 0 \text{ m/s}$

$v_f = ?$

$t = 0.100 \text{ s}$

$a = ?$

$$a = \frac{F}{m} = \frac{|\vec{E}|q}{m}$$

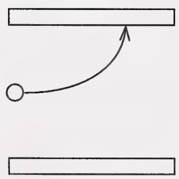
$$a = \frac{v_f - v_i}{t}$$

$$v_f = v_i + at$$

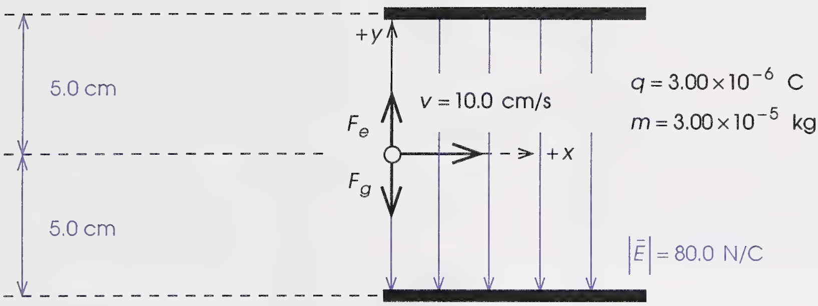
Combine the equations.

$$\begin{aligned} v_f &= v_i + \frac{|\vec{E}|qt}{m} \\ &= 0 \text{ m/s} + \frac{(80.0 \text{ N/C})(3.00 \times 10^{-6} \text{ C})(0.100 \text{ s})}{3.00 \times 10^{-5} \text{ kg}} \\ &= 0.800 \text{ m/s} \end{aligned}$$

f.



25. a.



b. Horizontally the object will move with uniform motion since no forces act in this direction. Vertically the object will move with accelerated motion in the direction of the net force.

c. $q = 3.00 \times 10^{-6}\ \text{C}$

$m = 3.00 \times 10^{-5}\ \text{kg}$

$g = 9.81\ \text{m/s}^2$

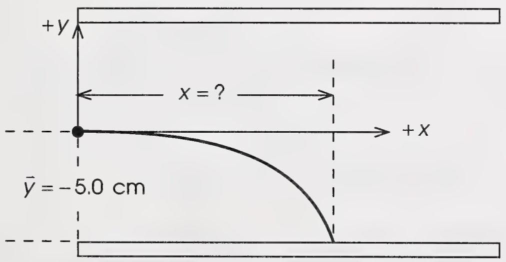
$|\vec{E}| = 80.0\ \text{N/C}$

$\vec{F}_{net} = ?$

$$\vec{F}_{net} = \vec{F}_e + \vec{F}_g$$
$$|\vec{F}_{net}| = |\vec{F}_e| - |\vec{F}_g|$$
$$= |\vec{E}|q - mg$$
$$= (80.0\ \text{N/C})(3.00 \times 10^{-6}\ \text{C}) - (3.00 \times 10^{-5}\ \text{kg})(9.81\ \text{m/s}^2)$$
$$= -5.43 \times 10^{-5}\ \text{N}$$
$$\vec{F}_{net} = 5.43 \times 10^{-5}\ \text{N, down}$$

d. The object will hit the bottom (negative) plate.

e. This part of the problem is particularly challenging to solve. The key is to think in terms of projectile motion.



The particle will follow a parabolic path, with the *x*- and *y*-components of the motion acting independently. The strategy is to find the time needed to travel the vertical distance first. Since this is the same as the time to travel horizontally, you can then use this value to find the horizontal distance.

Vertically:

$\vec{y} = -5.0 \text{ cm}$

$(v_y)_i = 0$

$\vec{a}_y = ?$

$t = ?$

$$\vec{y} = (\vec{v}_y)_i t + \frac{1}{2}(\vec{a}_y)t^2$$

$$\vec{y} = \frac{1}{2}(\vec{a}_y)t^2$$

$$t = \sqrt{\frac{2\vec{y}}{(\vec{a}_y)}}$$

$$= \sqrt{\frac{2\vec{y}}{\left(\frac{\vec{F}_{net}}{m}\right)}}$$

$$= \sqrt{\frac{2(-5.0 \times 10^{-2} \text{ m})}{-\left(\frac{5.43 \times 10^{-5} \text{ N}}{3.00 \times 10^{-5} \text{ kg}}\right)}}$$

$$= 0.235 \text{ s}$$

$$\vec{F}_{net} = m\vec{a}$$

$$\vec{a} = \frac{\vec{F}_{net}}{m}$$

Substitute.

Horizontally:

$\vec{x} = ?$

$t = 0.235 \text{ s}$

$\vec{v}_x = 10.0 \text{ cm/s}$

$$\vec{v}_x = \frac{\vec{x}}{t}$$

$$\vec{x} = \vec{v}_x t$$

$$= (10.0 \text{ cm/s})(0.235 \text{ s})$$

$$= 2.35 \text{ cm}$$

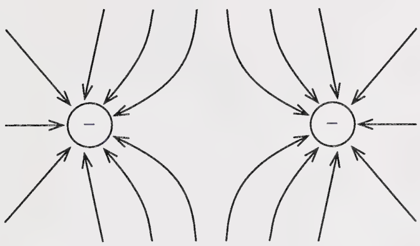
Section 3: Activity 3

1. An electric field line is an imaginary line that shows the direction of the electric field around a charged object. For each point along the line, the electric field vector would be a tangent drawn to the electric field line.

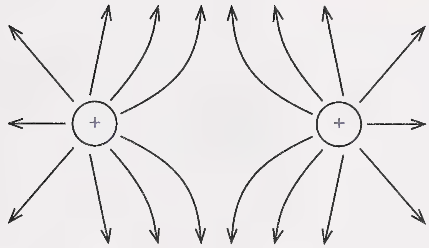
2. Electric field lines are helpful because they give an overall picture of the field and they indicate how a positive test charge would behave in the region around the sources.

3. An electric field line shows the way that a positive test charge would go if it were placed in a spot. The field lines can also indicate the strength of the electric field. Where more field lines are crowded together the electric field is stronger.

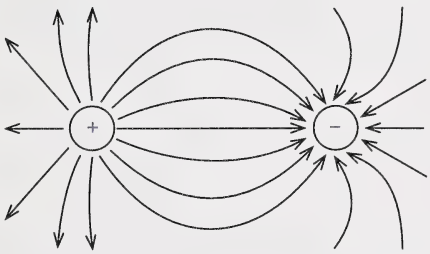
4. a.



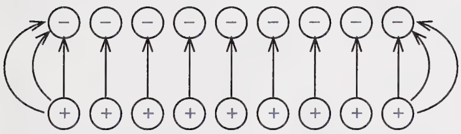
b.



c.

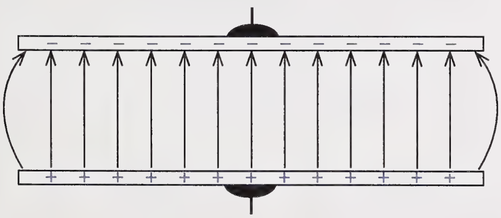


5.



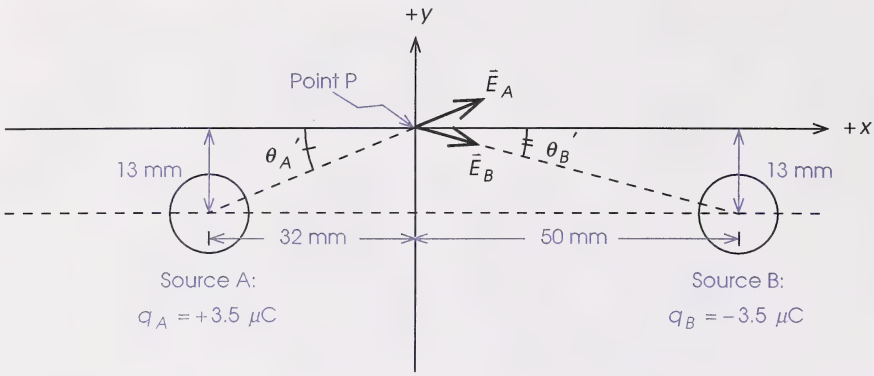
The net effect in the region in the middle is for the field lines to run parallel to each other. The reason is that the horizontal components of one charge's electric field lines are cancelled by the horizontal components of another. The only place that this does not occur is on the edges where there are no charges left on the outside to cancel the horizontal components.

6.



The reasoning behind this question is identical to that used to answer the previous question.

7 a.



b. Between A and point P:

$$\begin{aligned} C^2 &= A^2 + B^2 \\ &= (13\text{ mm})^2 + (32\text{ mm})^2 \\ &= 1193\text{ mm}^2 \\ C &= 34.54\text{ mm} \\ &= 35\text{ mm} \end{aligned}$$

Between B and point P:

$$\begin{aligned} C^2 &= A^2 + B^2 \\ &= (13\text{ mm})^2 + (50\text{ mm})^2 \\ &= 2669\text{ mm}^2 \\ C &= 51.66\text{ mm} \\ &= 52\text{ mm} \end{aligned}$$

c. $$\begin{aligned} \tan\theta_A' &= \frac{13\text{ mm}}{32\text{ mm}} \\ &= 0.4063 \\ \theta_A' &= 22.1° \end{aligned}$$

$$\begin{aligned} \tan\theta_B' &= \frac{13\text{ mm}}{50\text{ mm}} \\ &= 0.2600 \\ \theta_B' &= 14.6° \end{aligned}$$

As measured from the positive x-axis:

$$\begin{aligned} \theta_A &= 180° + \theta_A' \\ &= 180° + 22.1° \\ &= 202.1° \\ &= 202° \end{aligned}$$

As measured from the positive x-axis:

$$\begin{aligned} \theta_B &= 360° - \theta_B' \\ &= 360° - 14.6° \\ &= 345.4° \\ &= 345° \end{aligned}$$

d. $q_A = +3.5\ \mu\text{C} = +3.5\times10^{-6}\text{ C}$

$r = 34.54\text{ mm} = 3.454\times10^{-2}\text{ m}$

$|\vec{E}_A| = ?$

$$\begin{aligned} |\vec{E}_A| &= \frac{kq_A}{r^2} \\ &= \frac{(8.99\times10^9\text{ N}\bullet\text{m}^2/\text{C}^2)(3.5\times10^{-6}\text{ C})}{(3.454\times10^{-2}\text{ m})^2} \\ &= 2.64\times10^7\text{ N/C} \\ &= 2.6\times10^7\text{ N/C} \end{aligned}$$

$q_B = -3.5\ \mu C = -3.5 \times 10^{-6}\ C$

$r = 51.66\ \text{mm} = 51.66 \times 10^{-2}\ \text{m}$

$|\vec{E}_B| = ?$

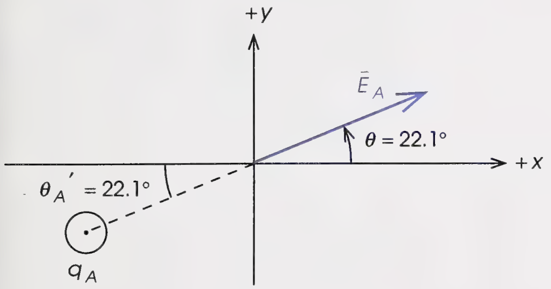
$$|\vec{E}_B| = \frac{kq_B}{r^2}$$

$$= \frac{(8.99 \times 10^9\ \text{N} \bullet \text{m}^2/\text{C}^2)(3.5 \times 10^{-6}\ \text{C})}{(5.166 \times 10^{-2}\ \text{m})^2}$$

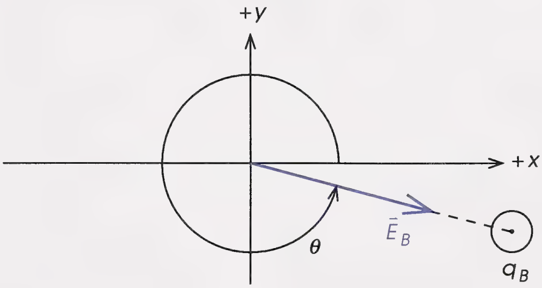
$$= 1.18 \times 10^7\ \text{N/C}$$

$$= 1.2 \times 10^7\ \text{N/C}$$

e. In each case the directions are determined by the way that a positive test charge would go. This is shown in the diagram for the solution to question 7.a.



$\theta = 22.1°$



$\theta = 345°$

f. Step 1: Find the x- and y-components of each field.

$|\vec{E}_A| = 2.64 \times 10^7\ \text{N/C}$

$$|\vec{E}_A|_x = |\vec{E}_A| \cos\theta$$
$$= (2.64 \times 10^7\ \text{N/C})(\cos 22.1°)$$
$$= 2.45 \times 10^7\ \text{N/C}$$

$$|\vec{E}_A|_y = |\vec{E}_A| \sin\theta$$
$$= (2.64 \times 10^7\ \text{N/C})(\sin 22.1°)$$
$$= 9.93 \times 10^6\ \text{N/C}$$

$|\vec{E}_B| = 1.18 \times 10^7\ \text{N/C}$

$$|\vec{E}_B|_x = |\vec{E}_B| \cos\theta$$
$$= (1.18 \times 10^7\ \text{N/C})(\cos 345°)$$
$$= 1.14 \times 10^7\ \text{N/C}$$

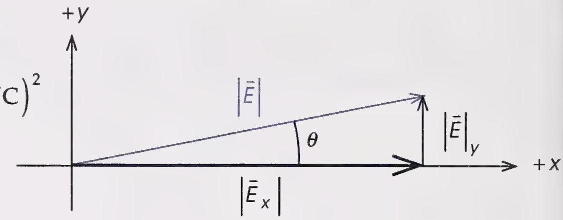
$$|\vec{E}_B|_y = |\vec{E}_B| \sin\theta$$
$$= (1.18 \times 10^7\ \text{N/C})(\sin 345°)$$
$$= -3.05 \times 10^6\ \text{N/C}$$

Step 2: Calculate the magnitude of the resultant.

$$\left|\vec{E}\right|_x = \left|\vec{E}_A\right|_x + \left|\vec{E}_B\right|_x$$
$$= \left(2.45\times10^7\ \text{N/C}\right) + \left(1.14\times10^7\ \text{N/C}\right)$$
$$= 3.59\times10^7\ \text{N/C}$$

$$\left|\vec{E}\right|_y = \left|\vec{E}_A\right|_y + \left|\vec{E}_B\right|_y$$
$$= \left(9.93\times10^6\ \text{N/C}\right) + \left(-3.05\times10^6\ \text{N/C}\right)$$
$$= 6.88\times10^6\ \text{N/C}$$

$$\left|\vec{E}\right|^2 = \left|\vec{E}_x\right|^2 + \left|\vec{E}_y\right|^2$$
$$= \left(3.59\times10^7\ \text{N/C}\right)^2 + \left(6.88\times10^6\ \text{N/C}\right)^2$$
$$\left|\vec{E}\right| = 3.66\times10^7\ \text{N/C}$$
$$= 3.7\times10^7\ \text{N/C}$$



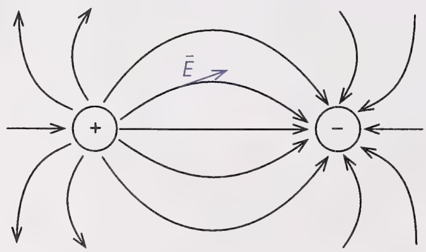
Step 3: Calculate the angle of the resultant.

$$\tan\theta = \frac{\left|\vec{E}\right|_y}{\left|\vec{E}\right|_x}$$
$$= \frac{\left(6.88\times10^6\ \text{N/C}\right)}{\left(3.59\times10^7\ \text{N/C}\right)}$$
$$= 0.1916$$
$$\theta = 10.8°$$
$$= 11°$$

Step 4: State the final answer.

$$\vec{E} = 3.7\times10^7\ \text{N/C, } 11°$$

g. Yes, the answer to this question should match the sketch done to answer question 4.c. The following diagram illustrates how the electric field vector at a point is a tangent drawn to the field line.

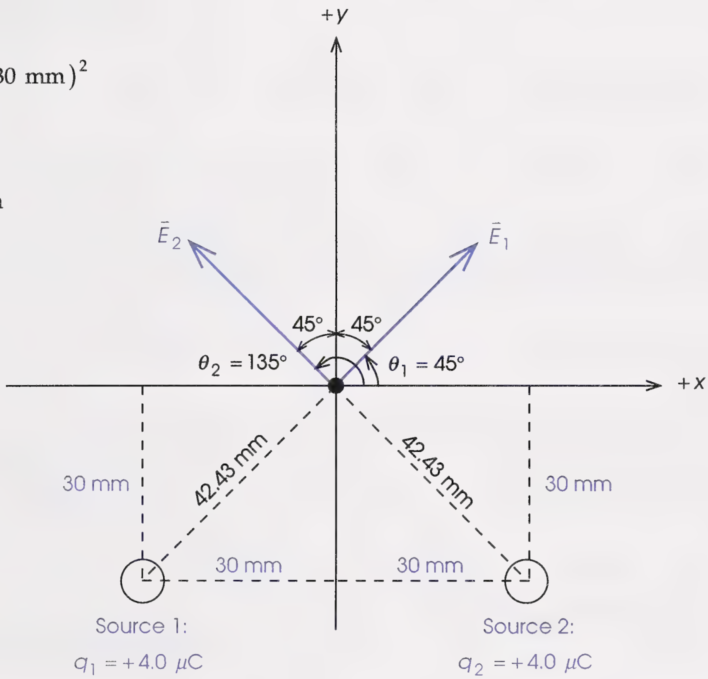


8. a. There are several things to note before starting this question:

- The field due to source 1 and the field due to source 2 will be identical in magnitude.
- Both fields will make an angle of 45° on either side of the y-axis.
- The previous two points mean that the x-components will cancel. The problem can be solved by finding the y-component of one and then multiplying by 2.

Step 1: Calculate the distance between each source and point P.

$$\begin{aligned} C^2 &= A^2 + B^2 \\ &= (30\ \text{mm})^2 + (30\ \text{mm})^2 \\ &= 1800\ \text{mm}^2 \\ C &= 42.43\ \text{mm} \\ &= 4.243 \times 10^{-2}\ \text{m} \end{aligned}$$

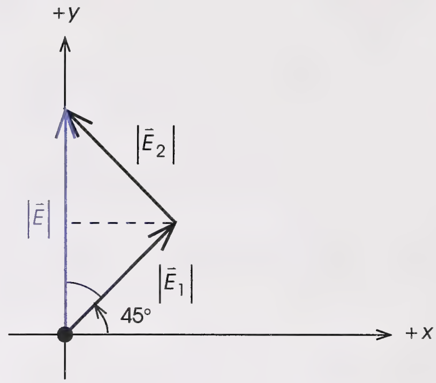


Step 2: Calculate the magnitude of one of the electric fields.

$$\begin{aligned} \left|\bar{E}_2\right| = \left|\bar{E}_1\right| &= \frac{kq_1}{r^2} \\ &= \frac{\left(8.99 \times 10^9\ \text{N}\bullet\text{m}^2/\text{C}^2\right)\left(4.0 \times 10^{-6}\ \text{C}\right)}{\left(4.243 \times 10^{-2}\ \text{m}\right)^2} \\ &= 1.997 \times 10^7\ \text{N/C} \end{aligned}$$

Step 3: Calculate the magnitude of the resultant.

$$\begin{aligned}|\vec{E}| &= 2|\vec{E}_1|_y \\ &= 2|\vec{E}_1|\sin\theta \\ &= 2(1.997\times10^7\ \text{N/C})(\sin 45°) \\ &= 2.82\times10^7\ \text{N/C} \\ &= 2.8\times10^7\ \text{N/C}\end{aligned}$$



Step 4: State the final answer.

$$\vec{E} = 2.8\times10^7\ \text{N/C, } 90°$$

b. Yes the answer to question 8.a. predicts the same direction as the answer to question 4.b.

9. There are several things to note before starting this question:

- The magnitude of the field due to source 1 and the field due to source 2 will be identical in magnitude.
- Both fields will be directed to the left.
- The previous two points mean that the solution will involve calculating one of the fields and then multiplying by 2.

$q_1 = -3.5\ \mu\text{C} = -3.5\times10^{-6}\ \text{C}$

$r = 44\ \text{mm} = 4.4\times10^{-2}\ \text{m}$

$|\vec{E}_1| = ?$

$$\begin{aligned}|\vec{E}_1| &= \frac{kq_1}{r^2} \\ &= \frac{(8.99\times10^9\ \text{N}\bullet\text{m}^2/\text{C}^2)(3.5\times10^{-6}\ \text{C})}{(4.4\times10^{-2}\ \text{m})^2} \\ &= 1.625\times10^7\ \text{N/C}\end{aligned}$$

$$\begin{aligned}|\vec{E}| &= 2|\vec{E}_1| \\ &= 2(1.625\times10^7\ \text{N/C}) \\ &= 3.25\times10^7\ \text{N/C}\end{aligned}$$

$\vec{E} = 3.25\times10^7\ \text{N/C}$, directed to the left

10. The electric field vectors of sources 1 and 4 cancel, since they are equal and opposite. The electric field vectors of sources 2 and 3 cancel, since they are equal and opposite. The overall result is that the electric field in the middle of the square at point P is zero.

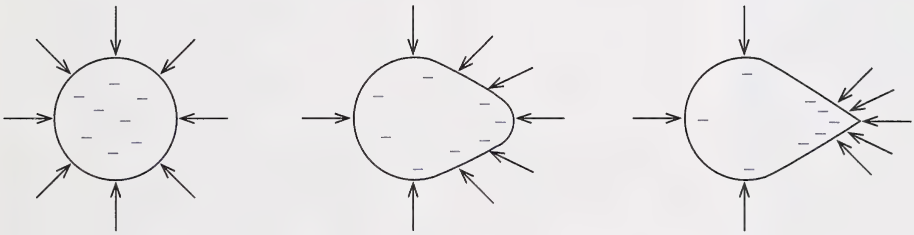
11.

12. The greatest concentration of field lines occurs just below the lowest part of the cloud. This is also in the region just above the building.

13. The lightning takes a jagged path because the negative charges are attracted to the pockets of positive charge which are randomly distributed throughout the atmosphere.

14. A lightning strike involves a large transfer of charge from the cloud to the ground. This removal of charge from the cloud would reduce the strength of the electric field within the cloud and allow the suspended raindrops to fall.

15.



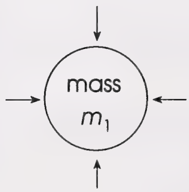
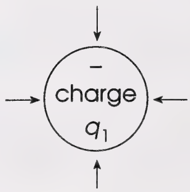
16. The positive ions in the air would be attracted to the region with the most intense concentration of field lines. This would be at the pointed end of the object on the far right.

17. The lightning rod actually allows the transfer of charge between the ground and the cloud to take place in a safe manner. This partially discharges the region of the cloud immediately above the lightning rod, which reduces the possibility of a lightning strike.

Section 3: Follow-up Activities

Extra Help

1.

Question	Gravitational Field	Electric Field
What is the definition of the field?	The space surrounding a mass in which other masses within the region will experience a gravitational force.	The space surrounding a charge in which other charges within the region will experience an electrostatic force.
What is the symbol given to the field?	$\bar{g}$	$\bar{E}$
What are the units of the field?	N/kg or m/s^2	N/C
What two equations are used to calculate the magnitude of the field?	$g = \frac{Gm_1}{r^2}$ $g = \frac{F_g}{m}$	$\lvert\bar{E}\rvert = \frac{kq_1}{r^2}$ $\lvert\bar{E}\rvert = \frac{F_e}{q}$
How is the direction of the field defined?	The direction is towards the centre of the mass producing the field.	The direction is the direction of the force on a small positive test charge.
Sketch the direction of the field around the object .		

2. A test mass is a small mass that is brought into a gravitational field to determine the magnitude and direction of the gravitational field produced by a larger mass. Similarly a test charge is a small positive charge that is brought into an electric field to determine the magnitude and direction of the electric field produced by a larger charge.

3. You use a small test charge so that it does not affect the field of the charge whose field you are trying to determine.

4. $|\vec{E}| = ?$

$q_1 = -8.5\ \mu C = -8.5 \times 10^{-6}\ C$

$r = 95\ mm = 9.5 \times 10^{-2}\ m$

$$|\vec{E}| = \frac{kq_1}{r^2}$$
$$= \frac{(8.99 \times 10^9\ N \bullet m^2/C^2)(8.5 \times 10^{-6}\ C)}{(9.5 \times 10^{-2}\ m)^2}$$
$$= 8.47 \times 10^6\ N/C$$
$$= 8.5 \times 10^6\ N/C$$

5. $|\vec{E}| = ?$

$q_2 = 1.5\ \mu C = 1.5 \times 10^{-6}\ C$

$q_1 = 8.5\ \mu C = 8.5 \times 10^{-6}\ C$

$r = 95\ mm = 9.5 \times 10^{-2}\ m$

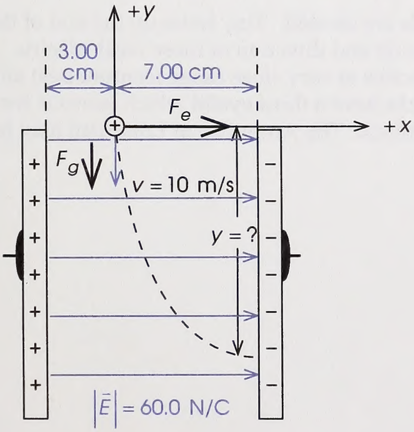
$$F_e = \frac{kq_2q_1}{r^2}$$
$$= \frac{(8.99 \times 10^9\ N \bullet m^2/C^2)(1.5 \times 10^{-6}\ C)(8.5 \times 10^{-6}\ C)}{(9.5 \times 10^{-2}\ m)^2}$$
$$= 12.7\ N$$
$$= 13\ N$$

$$|\vec{E}| = \frac{F_e}{q_2}$$
$$= \frac{12.7\ N}{(1.5 \times 10^{-6}\ C)}$$
$$= 8.47 \times 10^6\ N/C$$
$$= 8.5 \times 10^6\ N/C$$

6. The direction would be towards the source because this is the direction that a positive test charge would be forced.

Enrichment

1.



$m = 5.00\ mg$

$q = 7.50\ \mu C = 7.50 \times 10^{-6}\ C$

In this problem the particle experiences an unbalanced force and therefore an acceleration in both the horizontal and vertical directions.

Horizontally:

$$F = F_e$$
$$ma = q\left|\vec{E}\right|$$
$$a = \frac{q\left|\vec{E}\right|}{m}$$

Vertically:

$$F = F_g = mg$$
$$v_i = 10 \text{ m/s}$$
$$y = \left(v_y\right)_i t + \frac{1}{2}gt^2$$

The solution is to use the horizontal motion to solve for time and then substitute this value into the vertical equations.

Horizontally:

$$x = \left(v_x\right)_i t + \frac{1}{2}a_x t^2$$
$$x = \frac{1}{2}a_x t^2$$
$$t = \sqrt{\frac{2x}{a_x}}$$
$$= \sqrt{\frac{2x}{\left(\frac{q\left|\vec{E}\right|}{m}\right)}}$$
$$= \sqrt{\frac{2(0.0700 \text{ m})}{\left(\frac{\left(7.5\times10^{-6} \text{ C}\right)(60.0 \text{ N/C})}{5.00\times10^{-6} \text{ kg}}\right)}}$$
$$t = 3.94\times10^{-2} \text{ s}$$

Vertically:

$$y = \left(v_y\right)_i t + \frac{1}{2}gt^2$$
$$= (10 \text{ m/s})\left(3.94\times10^{-2} \text{ s}\right) + \frac{1}{2}\left(9.81 \text{ m/s}^2\right)\left(3.94\times10^{-2} \text{ s}\right)^2$$
$$= \left(3.94\times10^{-1} \text{ m}\right) + \left(7.61\times10^{-3} \text{ m}\right)$$
$$= 0.40\,161 \text{ m}$$
$$= 0.40 \text{ m}$$

2. When muscles of animals expand and contract, weak electric fields are created. Tiny holes on the end of the shark's head, called Ampullae of Lorenzini, can detect the magnitude and direction of these weak electric fields and help guide the shark to the prey. This sense is only effective at very close range (centimetres) and may be the final way that a shark is guided to its prey. Many sharks have a third eyelid which protects the eyeball during an attack on its prey, but it temporarily blinds the shark. The Ampullae of Lorenzini may help the shark find its food in these circumstances.

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Module 3

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